THE COLLEGE OF EARTH AND MINERAL SCIENCES

The Variation of the Angle of Internal Friction with Size Consist for Mechanically-Chipped Material

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The Variation of the Angle of Internal Friction with Size Consist for Mechanically-Chipped Material

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13. ABSTRACT

In order to improve aspects of materials handling in the rapid excavation process, research is underway to characterize the muck from mechanical tunnel boring machines. The specific project involves the correlation of the angle of internal friction, ϕ, to the size consist, often termed gradation, of this mechanically-chipped material. Existing references demonstrate that this angle depends upon mineral type, and for a given mineral type upon size of particles. Particle shape is usually a function of mineralogical character and is not as important a parameter in influencing this angle. Seven samples collected from tunnels located throughout the U. S. have been analyzed for gradation. Three of the samples have been completly tested for the angle of internal friction using a triaxial testing system. Tests to date suggest that disc cutters are better than rollers in tunneling machines, and that the angle of internal friction increases with a decrease in particle size.

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Technical Report Summary

Recent advances in tunneling with mechanical moles have induced the need for technical improvements in related areas. This report deals with an aspect of one of these areas, namely materials handling. Specifically, the problem investigated involves the interrelationships between variations in particle sizes of muck samples and changes in the angle of internal friction.

Samples were taken from seven tunnels located throughout the United States. A gradation analysis was run on all seven of the samples, and complete triaxial testing was performed on three of the samples. It was decided that the triaxial test would be used throughout in determining the angle of internal friction. Shear box tests could be used to correlate results. In addition to triaxial cells, a load cell, linear potentiometer, input conditioner, D.C. power supply, vacuum pump, oxygen tank for glycerin storage, and hydraulic press were among the equipment used in testing.

Results of the tests performed indicate that the angle of internal friction decreases with an increase in particle size in the small size range. Problems of membrane puncture have stifled testing of larger particle size. It is expected that this problem will soon be solved, allowing for a wider range of testing during the second year of testing.

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I. Introduction

PURPOSE OF THE RESEARCH

As the use of tunneling machines for drilling water, sewer, and transportation tunnels increases, the need for related technological improvements also increases. A major inefficient discipline in need of improvement is materials handling. The specific purpose of this research is therefore to determine if the handling characteristics of the muck from tunnel boring machines working in hard rock vary with particle size (Saperstein, 1970).

The specific handling characteristic examined here is the angle of internal friction. This angle is actually a number analogous to the coefficient of sliding friction, which relates the shear strength of a granular material to the normal force acting on it. "Angle" and "strength" are consequently often used interchangeably, i.e. a material with a high angle of internal friction has a high strength, and vice versa. Since the angle of internal friction is an independent parameter in many materials handling equations, research into the variation of this angle with particle size is well founded (Jenike; Pariseau and Pfleider; Saperstein, 1968).

PROBLEMS RESEARCHED

Since the purpose of this research centers around tunneling machines, muck samples from seven tunneling sites were gathered. Although the main problem researched was the variation of muck strength with size consist, tangential studies were also pursued. The sieve analysis, for example, yielded some very pertinent relationships between rock type, machine and bit type, and size gradation of the muck produced. An analysis of these

relationships is available in Section V of this paper.

Having visited several tunnel sites, gathered samples, and analyzed these samples, the investigators of this project are in a good position to compare and put into perspective various tunneling problems. It is expected that this new outlook will enhance sample gathering and tunnel problem analysis on the second sample gathering tour.

SCOPE

All testing and resulting conclusions are based upon the seven tunnels from which samples were gathered. Although delays in progress (due to unavailability of certain materials needed in equipment construction, and testing problems such as membrane puncture) made complete testing of all available samples impossible, some conclusions can be drawn from the results of the tests that were completed.

Since many more tests are to be conducted on a wider variety of samples during year two of the research project, the conclusions drawn in year one will be used as a guide for the continuing research during year two. This guidance, in conjunction with improved insight into the entire problem being researched, should lead to more detailed and conclusive results at the end of year two.

II. Theory of the Research

INTRODUCTION

Many factors have an effect on the ultimate results obtained in testing soil materials. It is therefore mandatory that sufficient consideration be given to each step of the test procedure in order that reproducible results may be achieved. A good understanding of the soil (or muck) characteristics involved, the sampling and sieving procedures used, and the testing method employed are prerequisites to actual sample collection and testing. Without a thorough understanding of these factors, erroneous testing results are inevitable.

MUCK CHARACTERISTICS

Several terms are commonly used in the literature to categorize muck characteristics. Familiarization with these terms and characteristics is essential to good sampling and testing procedures as well as result interpretations.

Mineralogy and Particle Shape. It is well known from results of previous testing that mineralogy is a major factor which determines the characteristics of rock particles. Minerals of the same type will exhibit common frictional qualities even though their origins are different (Marachi, et al.). It is therefore more important, in predicting handling characteristics, to be aware of the mineralogical constituents of the sample being tested than it is to know where the sample came from.

Particle shape and angularity also affect the angle of internal friction. Angular particles have a higher angle of internal friction than do rounded

particles at a given void ratio (Marachi, et al.). However, Koerner (1970) states that particle shape and angularity is a function of mineralogy. Koerner also found that particle shape and angularity does not significantly vary with the size of the particles tested, so long as the mineralogy remains the same. It is therefore reasonable to consider only the mineralogy of the particles being tested and not to worry about particle shape, since the latter characteristic is dependent upon the former.

Size and Gradation. Former studies by Koerner (1970) and Kirkpatrick (1965) indicate that in small particle sizes the angle of internal friction decreases with an increase in particle size. Of the two components of the angle of internal friction ϕ, Kirkpatrick found the frictional component ϕ_f to be independent of particle size. It is postulated that the dilatancy component ϕ_d is the component that varies with size.

Marachi finds in his literature survey that a few large particles in a well-graded sample have little or no effect on the measured strength of the sample. However, as the proportion of the larger particles increase and the specimen-diameter-to-maximum-particle-size ratio approaches five to ten the larger particles increase the measured strength.

Pertaining to gradation, Marachi notes that at low densities the angle of internal friction of an uniformly-graded material is higher than that of a well-graded soil. At maximum densities, however, the opposite is true. Well-graded soil has a higher angle of internal friction than does uniformly-graded material.

Cohesion. All soils can be classed in one of two groups, cohesive or cohesionless. Cohesive soils exhibit cohesion, or attraction, between individual particles, whereas cohesionless soils do not. It is important

to know whether the soil being tested is cohesive or cohesionless since the method of testing each type is somewhat different from the other. Some soils are only partially cohesive. These are usually tested as though the material were cohesionless. The degree of cohesion can be measured by how high Mohr's envelope cuts the τ (shear) axis. Figure 1 shows Mohr's envelope for both a partially cohesive and cohesionless soil.

SAMPLING AND SIEVING

Several good A.S.T.M. references pertaining to sampling and sieving methods are available. Some of these can be found in the References of this paper. Generally, however, three basic steps may be followed in order to sample and sieve a specimen effectively.

Sampling. When a good representative sample of soil or muck is desired from a particular site, careful attention must be paid to size segregation. For example, taking a sample from a stock pile located in the open is a difficult method of obtaining a truly representative sample. Size segregation occurs during dumping, and then as the stock pile becomes subjected to weathering more segregation occurs.

A good place to sample a mining or tunneling machine is on a conveyor belt, or just as the muck passes over the tail pulley of the conveyor. Care must be taken that the muck on the entire width of a desired belt length be removed from the belt (Saperstein, 1970). Since size segregation occurs on conveyor belts, not following the above procedure gives a non-representative sample.

Coning and Quartering. Once the sample has been moved to the laboratory, it often becomes necessary to split the sample into several smaller groups. Coning and quartering is one method of doing this. The entire sample should be slowly dumped onto a smooth clean surface, forming a cone-

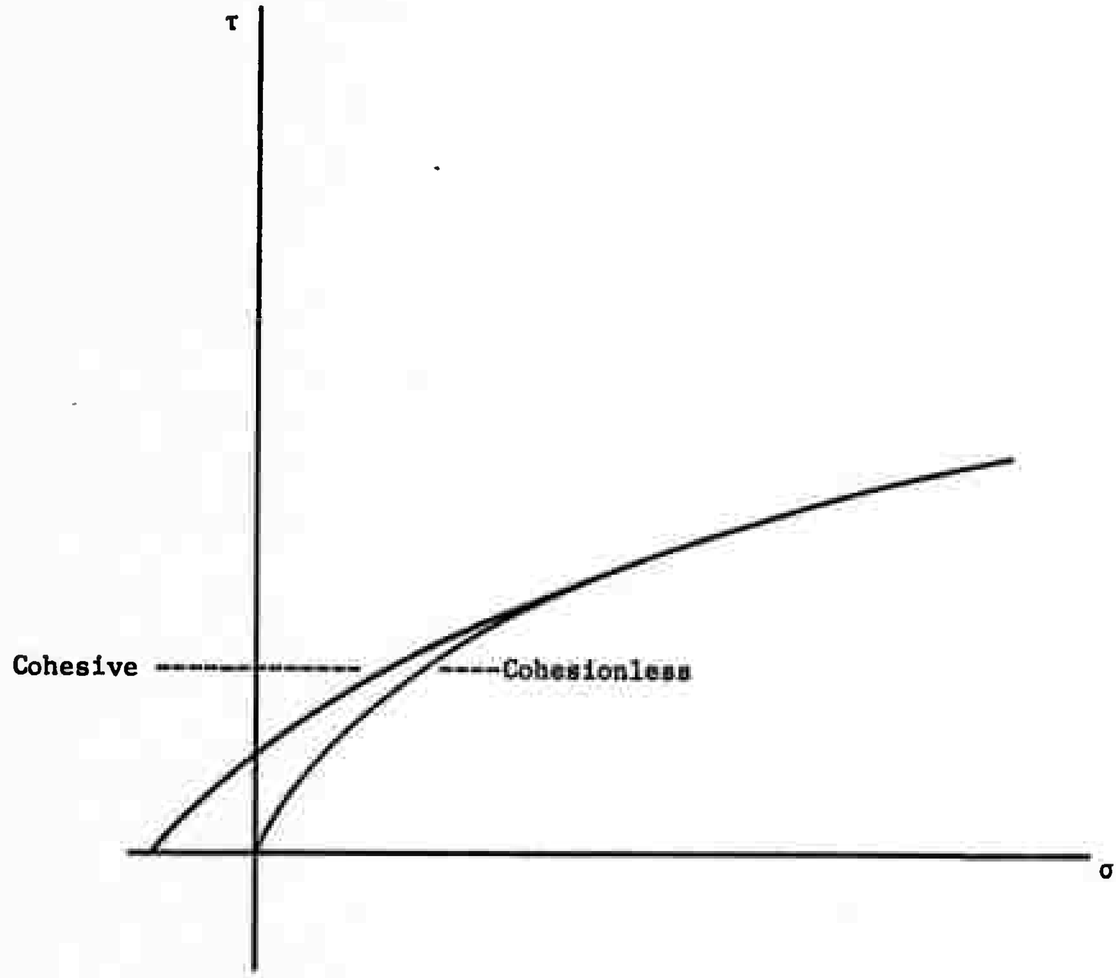

Figure 1. Mohr's envelope for cohesive and cohesionless soils.

shaped pile. A shovel may be used to scoop up any extra soil that may not have stayed in the pile. This soil should also be gently dropped onto the apex of the cone. At this point the cone should be shaped into a circle of uniform thickness by pulling soil from the center of the cone straight outward to the edge of the circle. This is done to all sides of the sample until a uniformly thick circle is achieved.

The circle must now be divided into four quarters by drawing a cross (+) through the center of the circle and pulling each quarter away from the rest of the sample. Each quarter of the sample now at hand is a good representative sample of the entire sample. Should these quarters still be too large for testing purposes, each quarter may be coned and quartered again for further subdivisions.

<u>Ro-tap and Sieve Use</u>. The use of ro-tap with 8-inch diameter sieves is a convenient way to sieve for gradation data, or for a large quantity of one particular size of particle. About 500 grams of a carefully weighed sample can be put on the top screen of a six-screen stack for each cycle in the ro-tap. After about 20 minutes in the ro-tap the screens are removed and the amount of sample on each screen is weighed. The soil in the bottom pan may be weighed and run through the cycle again using smaller mesh size screens. In this way data for sample gradation curves are obtained. Larger size material (>1/4 inch) can be sieved on gravel screens and shakers.

TESTING METHOD

Testing soils for the angle of internal friction can be done in several ways. The use of the triaxial cell is one effective way of obtaining this number. Selecting the proper size cell and following proper testing procedures are critical to good testing. One advantage of the triaxial cell over the

direct shear test is that the specimen being tested picks its own failure plane in the triaxial test, whereas the failure plane is predetermined in the direct shear test. Additionally, the principle stresses are known values throughout the triaxial test, whereas they are not throughout the direct shear test.

Equipment. By varying the confining pressure in the triaxial cell for each test, the load at failure will vary. In this manner the two values σ_1 and σ_3 are obtained for plotting Mohr's circle and ultimately the failure envelope. The angle of internal friction for cohesionless soils can be obtained from one test, but if cohesion is suspected, the envelope of several tests must be plotted. The size of the cell should be about six times the size of the largest particle to be tested. Marachi et al. found that as the size of the specimen gets larger than about 1/6 the size of the cell, the measured strength of the specimen increases, especially if the specimen contains a high proportion of these large particles.

Test Parameters. There are two basic types of triaxial tests, drained and undrained. In the drained test the water in the specimen being tested is permitted to drain throughout the test, thus keeping the pore pressure of the specimen down to zero. In the undrained test all valves to the specimen are closed. Subsequent confining pressure induces a pore pressure within the sample, since the water within the pores cannot escape. The measured shear strength of a specimen will be higher in a drained test than in an undrained test (Lambe). The reason for this can be clarified by an example. If 80 psi confining pressure causes a 30 psi pore pressure in an undrained specimen, the effective confining pressure can be considered to

be about 50 psi. The shear strength of a specimen is, of course, lower at 50 psi confining pressure than at 80 psi confining pressure.

Strain rate must be carefully controlled during triaxial tests. A rate of axial strain of 1% to 2% per minute is acceptable for most tests (Scott) of cohesionless material. At higher rates of strain in drained tests the water within the sample cannot drain fast enough, so a pore pressure is induced. This is especially true in specimens of small particle size, or with cohesive material.

Saturation of the specimen being tested also affects its strength in triaxial tests. It is therefore important that each sample being tested have the same degree of saturation, or that final calculations of strength take into account the degree of saturation.

Confining pressure affects density of the soil being tested. If a specimen is loosely packed but subjected to a high confining pressure, the confining pressure will have the effect of eliminating voids and thereby making the specimen more dense. Should the confining pressure be very high, the compressibility of the specimen becomes equal to the compressibility of solid particles (Lambe). It is possible to crush some specimen particles under high confining pressure, thereby creating a failure situation before axial load application even begins. According to Bishop and Eldin a complete variation in porosity for normal cohesionless sand will result in an approximate 10° change in the angle of internal friction. The prepared tests are not attempting to repeat his experiment, and therefore samples will be compacted to a state to approximate that which they experience under normal materials handling procedures.

All of the above factors and conditions must be carefully handled during laboratory work with soil materials. Sloppiness or failure to properly consider everything involved in the test can lead to erroneous and unreproducible results.

III. Test Procedure

INTRODUCTION

The proper methods of sampling and testing soils are discussed in the previous chapter. This chapter deals with the application of these methods to the collection and testing of muck samples from seven tunnel sites located in the United States and Canada.

SAMPLING AND SIEVING

A complete table of hard rock tunnels that were considered for sample collection purposes is available in the October 20, 1971 Semi-Annual Technical Report (Saperstein). An abbreviation of this table showing only those tunnels actually visited appears in Table 1. A more detailed table containing quite a bit of each tunnel's characteristics and drilling data appears in Appendix I.

Sampling and Splitting. In as many cases as possible samples were collected from the tunnels at the tail pulley of the conveyor belt. As has been mentioned earlier, sampling from a conveyor belt is generally good practice. Details pertaining to sampling at each particular tunnel site are available in Appendix II of the Semi-Annual Technical Report (Saperstein).

The total sample collected from each tunnel weighted approximately 50 pounds. Each sample was coned and quartered according to good splitting practice as discussed in the previous chapter. One-half of the sample was then set aside for possible future testing in the 6-inch cell. Of the remaining one-half sample, one-quarter was dried in an oven at 200° F for 24 hours and then part of this sample was sieved for a gradation analysis.

Name	Contractor	Diameter	Rock Type	Location	Completion	Machine
Queen Lane Raw Water Conduit	S & M Contractors	11'	Mica Schist & Quartz	Philadelphia	Aug. 71	Jarva Mark 11-1100
Navajo Irrigation	Bu. Rec. with Fluor Utah Eng. & Con.	20 1/2'	Sandstone	Farmington, N.M.	April 72	Dresser
Currant Creek	S. A. Healy Co. for Bureau Rec.	13'	Sandstone	Heber City, Utah	1972	Robbins 141-1
Toronto Interceptor Sewer	S. McNally & Sons, Ltd.	12'	Shale	Toronto	Fall 1971	Robbins 126
White Pine	self	18'	Sandstone	White Pine, Michigan	---	Robbins
Nast	Bureau Rec. with Peter Kiewit	10'	Granitic	Aspen, Colorado	---	Wirth
Lawrence Avenue	McHugh Construction	13'8"	Limestone	Chicago	October 71	Lawrence

Table I. Tunnels Sampled.

The remainder of the quarter was saved for "combined" (i.e, not sieved) testing in the 2.8-inch triaxial cell. After studying the results of the gradation analysis the individual sizes to be tested were selected. The remaining one-quarter of the entire sample was then sieved for bulk quantities of the individual sizes to be tested.

Sieving. Eleven 8-inch diameter brass U. S. Standard sieves were used in sieving all samples. The sieve sizes used were 2", 1", 0.5", 0.25" (3 mesh), 0.132" (6 mesh), 0.0661" (12 mesh), 0.0331" (20 mesh), 0.0165" (40 mesh), 0.0083" (70 mesh), 0.0041" (140 mesh), and 0.0021" (270 mesh). Every sample sieved passed the 2-inch sieve, so the maximum size sieve was properly chosen. Although a portion of each sample passed the 270-mesh-sieve into the bottom pan, smaller-opening sieves were not deemed necessary. Triaxial testing of size fractions would be done on the plus-270-mesh sizes since it is these sizes that can most easily be varied by altering tunneling machine parameters such as thrust and speed.

The sieving for gradation analysis was repeated four times for each tunnel sample. Since the results of the sieve analyses for each tunnel were always close, the results of the four tests were averaged together in each case.

The Triaxial System. The triaxial cell used in the testing is capable of handling specimens 1.4 inches in diameter and 7.5 inches long, and can be adapted to handle specimens 2.8 inches in diameter and 6 inches long. The cell was purchased from Soiltest, Inc. of Evanston, Illinois. It was decided not to purchase the confining pressure or loading system since available Penn State facilities could be adapted to serve these purposes. The pressure and electrical systems therefore had to be

designed and built before the actual testing began. A photograph of the entire testing system is shown in Figure 2. Visible are the 2.8 inch cell, the load cell, molds, the movable cart, the control panel, input conditioner, strip chart recorder, and a junction box.

Pressure System. A block diagram of the final pressure system design appears in Figure 3. An air supply capable of pressures up to 75 psi was used to pressurize the glycerin tank. A mobile cart was designed to carry the tank and an accompanying control panel. Since the loading system is a Baldwin hydraulic press used also in other research projects, the cart simplified the quick disengagement of the triaxial system from the press withouth disturbing the calibration of the system.

Four valves were used on the triaxial cell itself. Two of these were used for saturating the specimen with water. Water was permitted to enter through a valve to the bottom of the specimen. At saturation the water flowed out of the top of the specimen, through a valve, and into a bucket outside the system. At this point the water supply valve was closed, but the drainage valve remained open throughout the test. Since the degree of saturation affects the test results, it was decided to run all tests at 100% saturation in order to maintain uniformity. In that the muck coming from the face of a tunnel being bored can be quite wet since boring machines use water for cooling and dust control purposes, it was felt that saturation was a better simulation of actual conditions than testing dry. Any other state of moisture content would be difficult to simulate in as much as there is a rapid change of voids ratio near failure.

The valve on the top of the cell was used primarily for back pressure when draining the cell, or occasionally as a pressure release valve. The remaining valve at the base of the cell was used for glycerin filling and draining. Since the specimens tested never failed so

Figure 2. The Test System

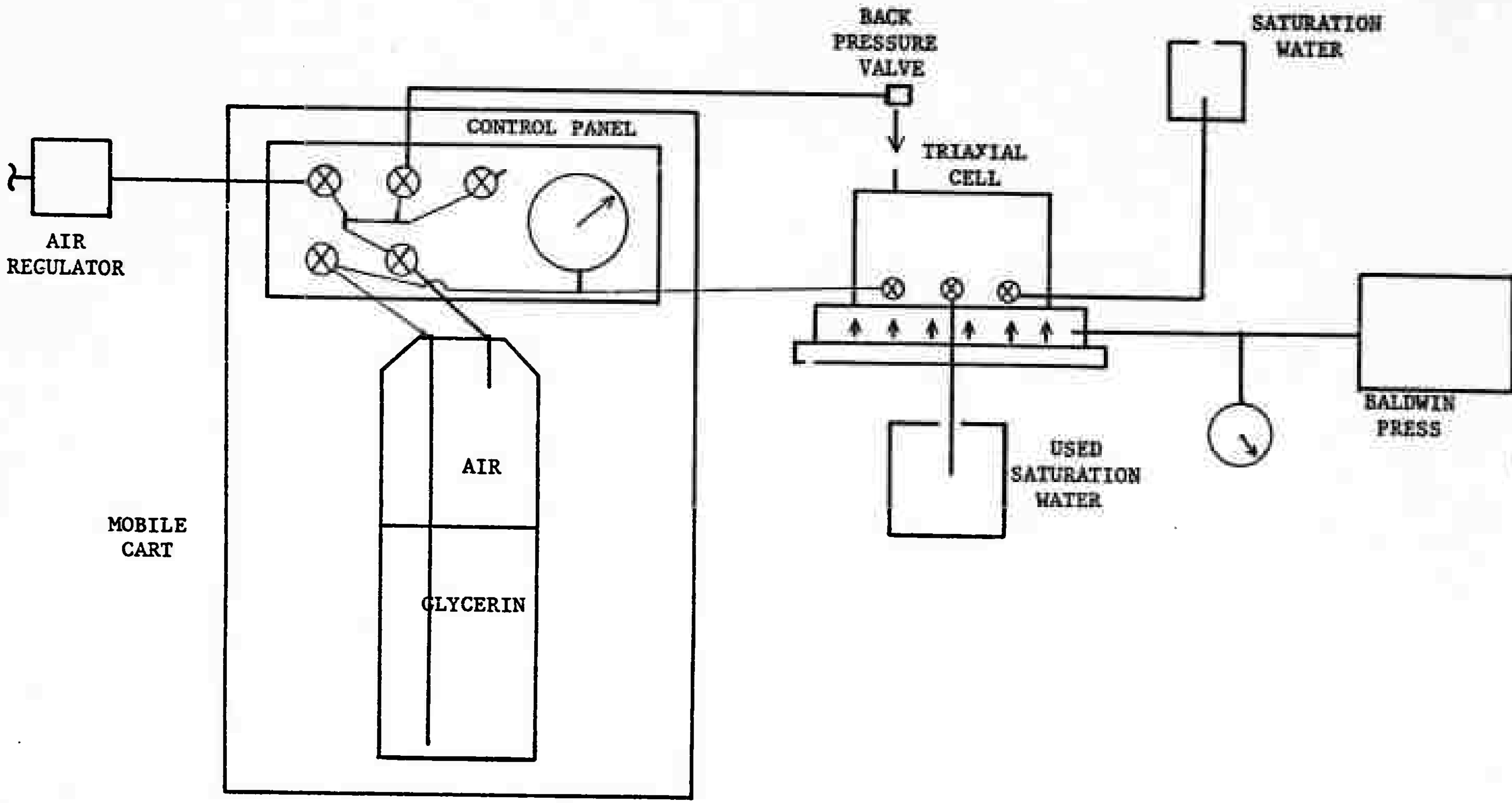

Figure 3. Block Diagram of the Pressure System.

dramatically as to contaminate the confining pressure fluid, the glycerin was always drained directly back into the glycerin tank. Filtering was not necessary.

Finally, a Baldwin press was used for axial load application. Although the press is equipped with a guage for measuring load, this was used only as a visual reference since the electrical system provided for this measurement.

Electrical System. A block diagram of the electrical system appears in Figure 4. Figure 5 is a more detailed schematic of the system. The two power supplies and the junction box are all located on the mobile cart. As can be seen in Figure 4, the entire electrical system can be unplugged from the load cell and linear potentiometer without disturbing the rest of the system.

The use of an input conditioner as a power supply for the load cell is very convenient. Calibration and zeroing features of the conditioner permit checks of the entire electrical system, even during a test, without disturbing the test itself. Both the input conditioner and the constant voltage power supply were maintained at 10 V D.C. for all tests. The scale settings on the chart recorder, however, were varied as needed throughout the testing program. By reducing the scale of the recorder output more accurate readings are possible for 1.4-inch, or low strength specimens. The scale must, of course, be increased for 2.8, or high strength specimens.

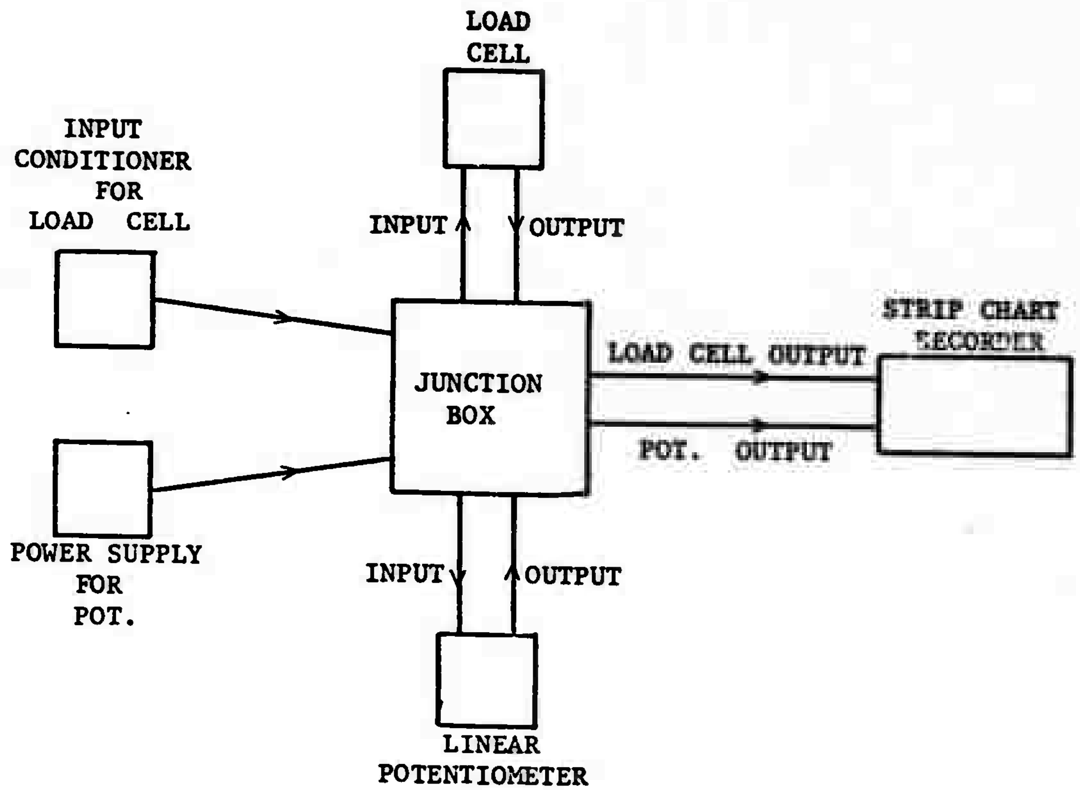

Figure 4. Block Diagram of the Electrical System.

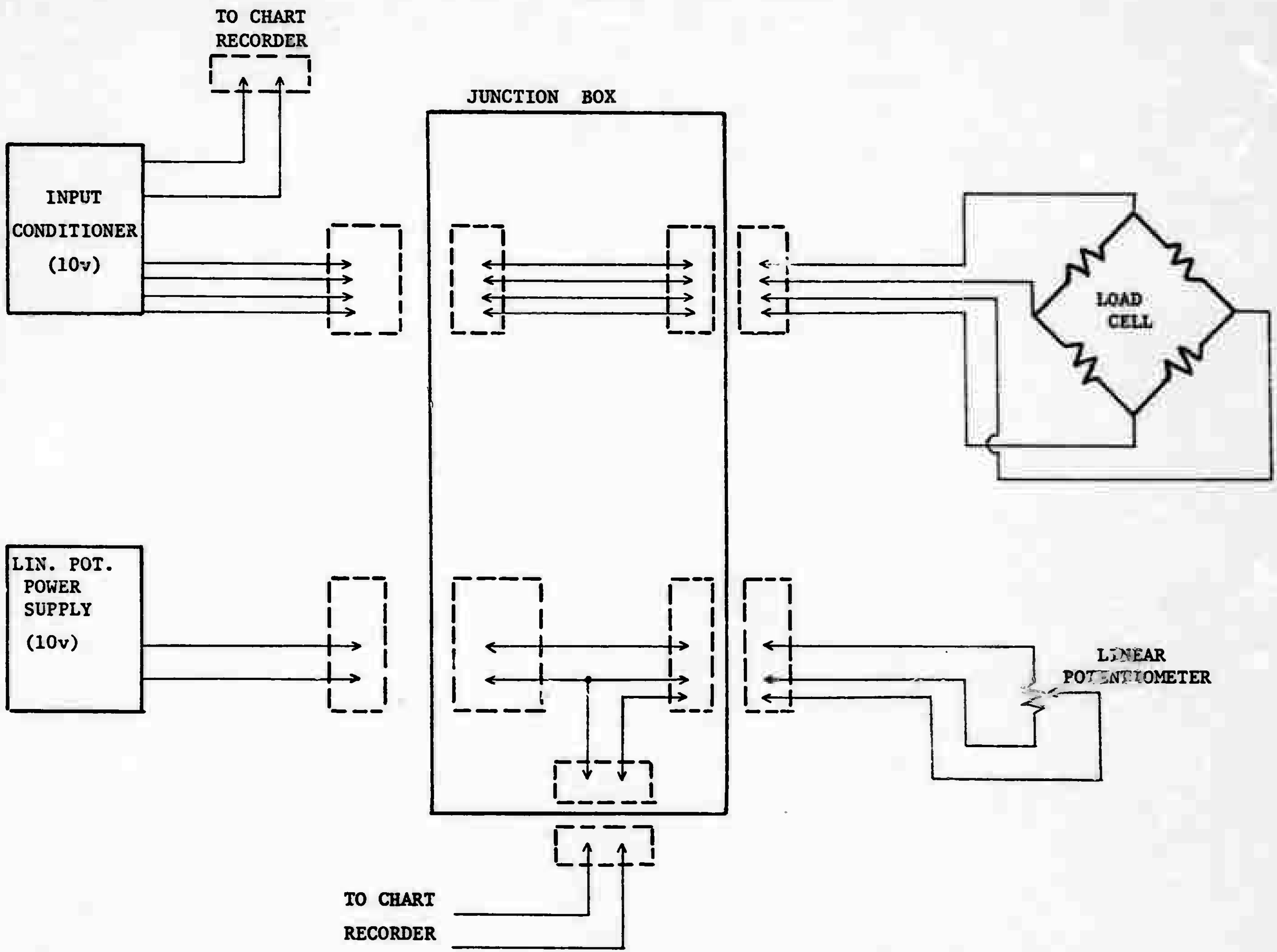

Figure 5. Schematic of the Electrical System.

Steps in Testing.

The testing procedure is unaffected by the size specimen or cell being used. A listing of the steps in testing is therefore common to every test performed.

1. The two rubber gaskets which seal the cell are cleaned, greased with high pressure vacuum grease, and seated in their proper grooves.

2. Grease is then applied to the sides of the brass base onto which a porous stone is placed.

3. A membrane is placed over the porous stone and brass base and sealed tight with rubber bands.

4. Next a mold is clamped around the membrane and the top of the membrane is folded over the top of the mold.

5. A vacuum pump is used to evacuate the air between the membrane and the mold in order to form a good cylinder.

6. The sample is placed within the membrane in 1/2 inch layers and gently tamped to the desired density. This tamping procedure is maintained constant for all samples and roughly approximates the compaction that would be received under normal handling; namely, that due to the impact experienced at transfer points. No attempt was made to achieve minimum porosity or overconsolidation.

7. The upper porous stone is then placed on top of the sample within the membrane.

8. Vacuum grease is then applied to the upper plate, placed on top of the porous stone, and sealed by the membrane with rubber bands again.

9. The vacuum pump is turned off and the mold is removed from the sample.

10. Final checks are made using a bubble level to insure that the specimen stands perfectly vertical and that the upper plate is horizontal.

11. Assembly of the triaxial cell is completed by properly positioning the cylindrical body of the cell and securely bolting down the cast iron top of the cell.

12. The Baldwin press is then adjusted so that the load cell just meets the fully extended loading piston, and the extended arm of the linear potentiometer just touches the top of the triaxial cell.

13. The specimen is saturated by opening the water supply valve and the drainage valve. When water starts to come out of the drainage valve the water supply is cut off and the specimen is allowed to equalize pore pressure to zero through the drainage valve.

14. Pressure is then applied to the glycerin tank and glycerin is permitted to flow into the cell until the specimen is entirely covered and the desired confining pressure is reached.

15. Pressure equilibrium between the glycerin tank and the triaxial cell is achieved and maintained throughout the test. (The cell and tank are open to each other during all tests.)

16. Final zeroing calibrations are applied to the chart recorder.

17. The Baldwin press is then turned on and the strain rate adjusted to about 1.5% per minute.

18. When the load recorded on the chart recorder begins to decrease despite continued axial strain the specimen is considered to have failed and the Baldwin press is turned off.

19. Air pressure is bled off of the top of the glycerin tank and back pressure is applied to the top of the triaxial cell. In this way the glycerin in the cell is forced back into the tank.

20. All pressures are reduced to zero and the triaxial cell is unbolted and opened up.

21. The specimen is removed and the entire apparatus is wiped clean in preparation for the next test.

IV. Results of the Tests

INTRODUCTION

Sieve analyses on all tunnel samples are complete and yield some interesting relationships between the tunneling machines (and bits) used and the particle size distributions created. Although triaxial testing of every sample has not yet been completed, enough testing has been done to make some observations and draw some conclusions. It is expected that further testing of a wider suite of samples will more solidly base these observations.

SIEVE ANALYSIS RESULTS

Table II tabulates the percent retained on each sieve for every sample tested. It should be noted that the percent retained on each sieve contains particles larger than the opening size of that sieve but smaller than the opening sizes of the next largest sieve. For example, the material retained on a 20-mesh sieve contains particles too large to pass a 0.84 mm opening, but small enough to pass a 1.68 mm opening. Additionally, the smallest dimension of the particle is the dimension that is measured. Since a particle that is 3" x 3/4" x 3/4" will pass a one-inch sieve, it is considered to be 1/2 inch in size, since the 1/2-inch sieve is the first sieve that it will not pass. Standard grain size distribution curves for each tunnel sample are plotted on semi-log paper and appear in Appendix II of this paper. Figure 6 shows the particle shape and angularity relationships for the seven tunnel sites sampled.

PERCENT RETAINED IN EACH SIEVE

Sieve Mesh	Philadelphia	Farmington	Heber City	Toronto	White Pine	Nast	Chicago
2"	0	0	0	0	0	0	0
1"	0	5.9	4.9	9.0	33.4	0	4.2
1/2"	8.1	8.8	10.7	38.6	16.9	4.1	22.2
3 mesh	4.5	7.2	12.7	11.2	25.7	7.8	26.2
6 mesh	8.3	5.6	15.6	15.7	5.2	10.3	15.0
12 mesh	8.4	3.9	15.6	11.0	3.5	12.1	10.5
20 mesh	10.0	6.8	11.8	5.7	2.5	11.4	6.0
40 mesh	12.5	18.7	8.3	3.0	2.0	11.8	3.7
70 mesh	17.9	21.7	5.9	1.6	2.3	11.2	1.8
140 mesh	15.9	11.8	6.0	1.1	3.9	9.7	1.2
270 mesh	7.2	5.2	3.9	0.8	2.3	7.2	1.9
Passed All Sieves	7.2	4.4	4.4	2.3	2.3	14.4	7.3

Table II. Tabulated Sieve Analysis.

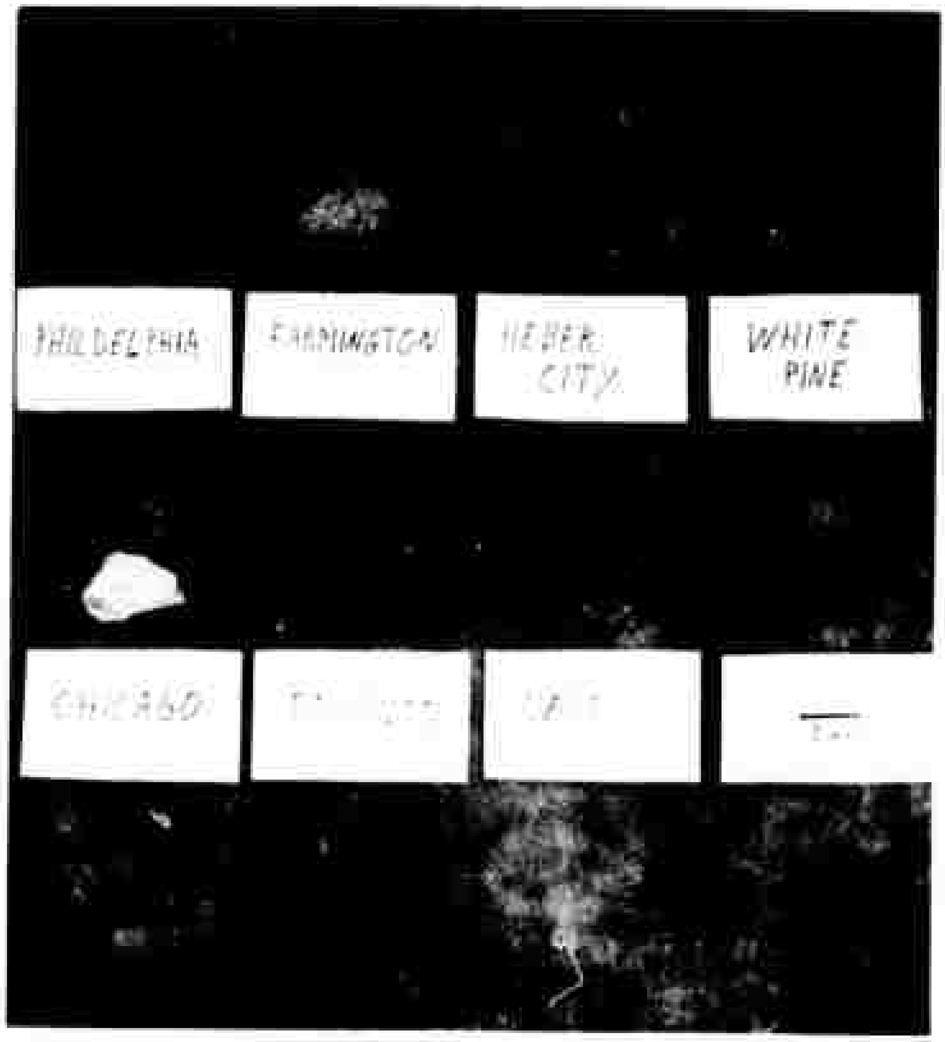

Figure 6. Particle shape of each sample.

TRIAXIAL TEST RESULTS

Data from all tests were taken on a strip chart recorder. Typical data taken on four individual tests are combined in Figure 7. The maximum load taken by the sample is read in milli-volts and then converted to psi. It is these loads in conjunction with the confining pressure loads that are used in drawing Mohr's Circles and the failure envelope. The complete set of all Mohr's Circles drawn from data taken in testing appears in Appendix III. Appendix IV shows the numerical data for each test.

Table III shows the angles of internal friction obtained by Mohr's Circle for combined triaxial testing and individual size fraction tests.

	Philadelphia	Farmington	Heber City
Combined	41.0°-45.0°	43.0°	0°
#6 mesh	31.5°	---	---
#12 mesh	---	---	24.0°
#40 mesh	34.5°	39.5°	0°
#140 mesh	35.5°	33.0°	0°

Table III. Tabulated Angles of Internal Friction.

Figure 8 on the following page shows a typical specimen before and after testing.

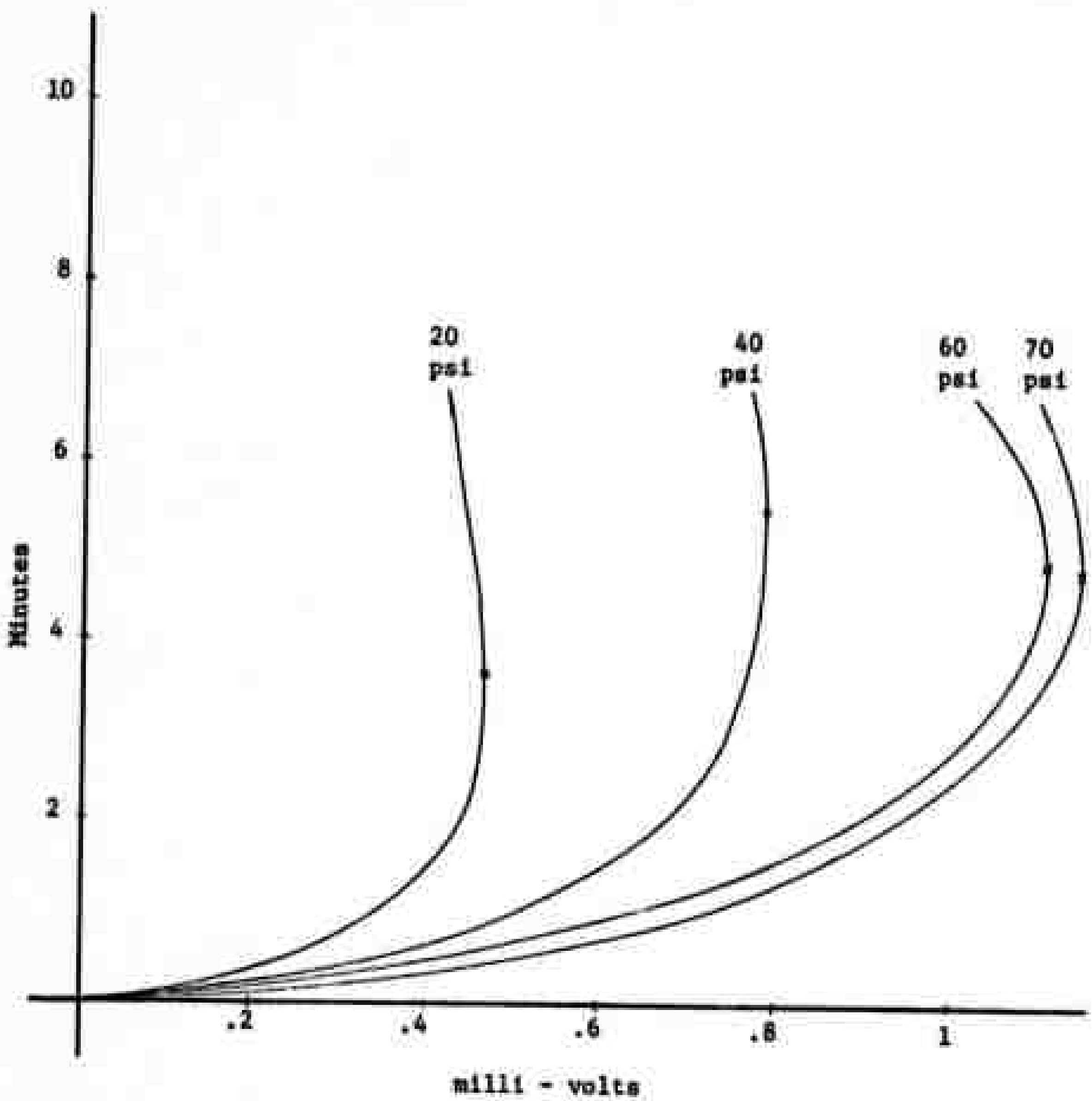

Figure 7. Typical Strip Chart Data.

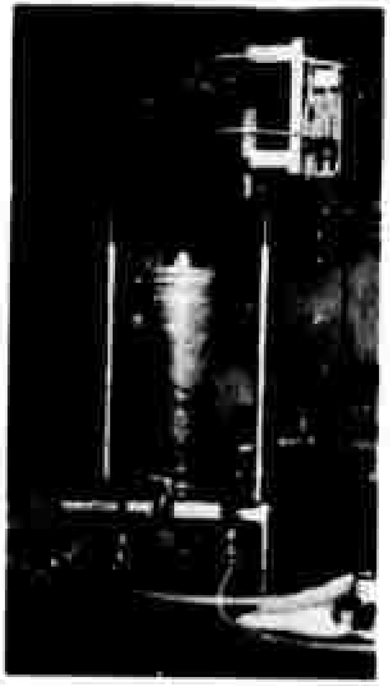

Figure 8(a). Specimen before testing.

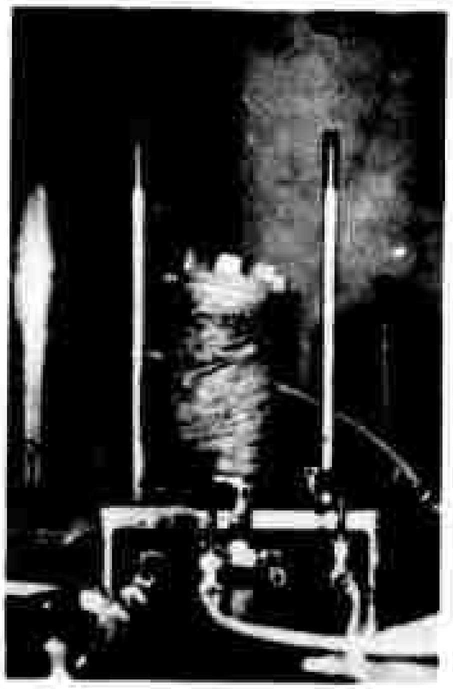

Figure 8(b). Specimen after failure.

V. Analysis, Observations, and Problems

INTRODUCTION

The tests performed to date yield some information pertaining to the geology of the individual tunnels and the machines used in boring them. Sieve analyses establish the gradation created by the machines, whereas the triaxial tests determine the strength. A statistical analysis of the Philadelphia material exemplifies the change in the angle of internal friction with particle size.

SIEVING

Table IV is a comparison of the rock, machine, and cutter type to the size muck created. Rock type does not appear to be the determining factor in size consist since sandstone particles varied from very large at White Pine to very small at Farmington. However, due to the limited number of samples available, this can only be called an observation. More shale, limestone, granite, and mica schist samples are needed for more conclusive results concerning rock type.

A very strong indication of Table IV is that disc cutters produce the largest muck particles whereas roller type cutters generally produce the smaller particles. The contrast between the White Pine and the Nast tunnels demonstrates this well. In the former about 50% of the material will not pass a 1-inch sieve, whereas in the latter 50% of the material will pass a 20-mesh sieve. Generally, the larger the particles created, the more efficient the entire system becomes.

Overall, very few problems were encountered in sieving. In some cases, such as the Chicago material, the sample had been idle for seven

Table IV. Comparison of Machine Type and Rock Size

Tunnel	Machine	Cutter	Rock Type	Smallest Sieve Through Which More Than 50% Passed
White Pine	Robbins 181-122	47 Disc	Sandstone	1"
Toronto	Robbins 126	25-30 Disc	Shale	1/2"
Chicago	Lawrence 0007	27 Disc with Button Mount	Dolomitic Limestone	1/2"
Heber City	Robbins 141-127	29 Disc	Sandstone	6
Nast	Wirth 600	26 Button Rollers	Granite	20
Farmington	Dresser	36 Double Disc	Sandstone	20
Philadelphia	Jarva Mark 4	27 Disc Kerf	Mica Schist	20

months after it was collected. This delay was due to equipment construction and the testing of other samples. During that time a 1/4-inch layer of very fine silty clay material formed on the top of the sample. This was due to upward migration and partial evaporation of water. During sieving most of this silty layer broke down, but quite a bit of it remained on sieves as large as 3 mesh. Saturation before triaxial testing will undoubtedly break these pieces down to their unconsolidated state. Triaxial testing of individual sizes such as 3 mesh may consequently give slightly distorted results since some very fine material will also be present.

When sieving of the Philadelphia material was completed each size fraction was noted to be very clean. On other samples such as Heber City, however, even the very large rocks were still covered with a powdery dust after sieving. Since total surface area increases with a decrease in the size of particles, the 40-mesh material is likely to contain a great deal of this dust. Once again, saturation is likely to affect the results of triaxial testing results.

TRIAXIAL TESTING

Of the three samples completely tested, the Philadelphia material most closely approached the expected results. As can be seen in Table III, the "combined" angle of internal friction is much higher than any individual size fraction. Also, the angle of internal friction is found to decrease with increasing size. More detailed data on this change in angle with size is available in the next section.

The combined Farmington material also showed a high angle of internal friction, with the individual size fractions having a lower angle. Membrane puncture on the larger sizes (6 and 12 mesh) is a serious problem in the

Farmington material. This problem also occurs in other tunnel samples when the size being tested exceeds 12 mesh and the confining pressure exceeds 40 psi. The reason for the decrease in the angle of internal friction between 40 mesh and 140 mesh is not wholly understood at this time. Further testing of the Farmington material is necessary to determine whether this apparent "reverse" change in angle size is due to an error in testing or an irregularity in the strength characteristics of the material.

The Heber City material shows no strength except in the testing of the 12 mesh size. Although the tunnel is mostly in sandstone, the sample tested was taken when the machine was in a fault zone of wet conglomerate and clay. When saturated this cohesive clayey sample loses all of its strength. The 12 mesh size shows some strength, probably due to a minimal amount of very fine sand in each sample tested. As was noted in the last section, the smaller the particle size, the more the surface area and consequently the more the quantity of fine material associated with each sample. 12 mesh is, of course, fairly large and might be expected to exhibit some strength even though the smaller sizes and combined sample do not.

STATISTICAL DATA ANALYSIS

Although a detailed statistical analysis of the variation of the angle of internal friction with size hardly seems necessary for the data now available, an analysis was performed to establish procedure. An IBM 360 computer was used to analyze the Philadelphia material tested. A graph showing the change in angle with particle size is shown in Figure 9.

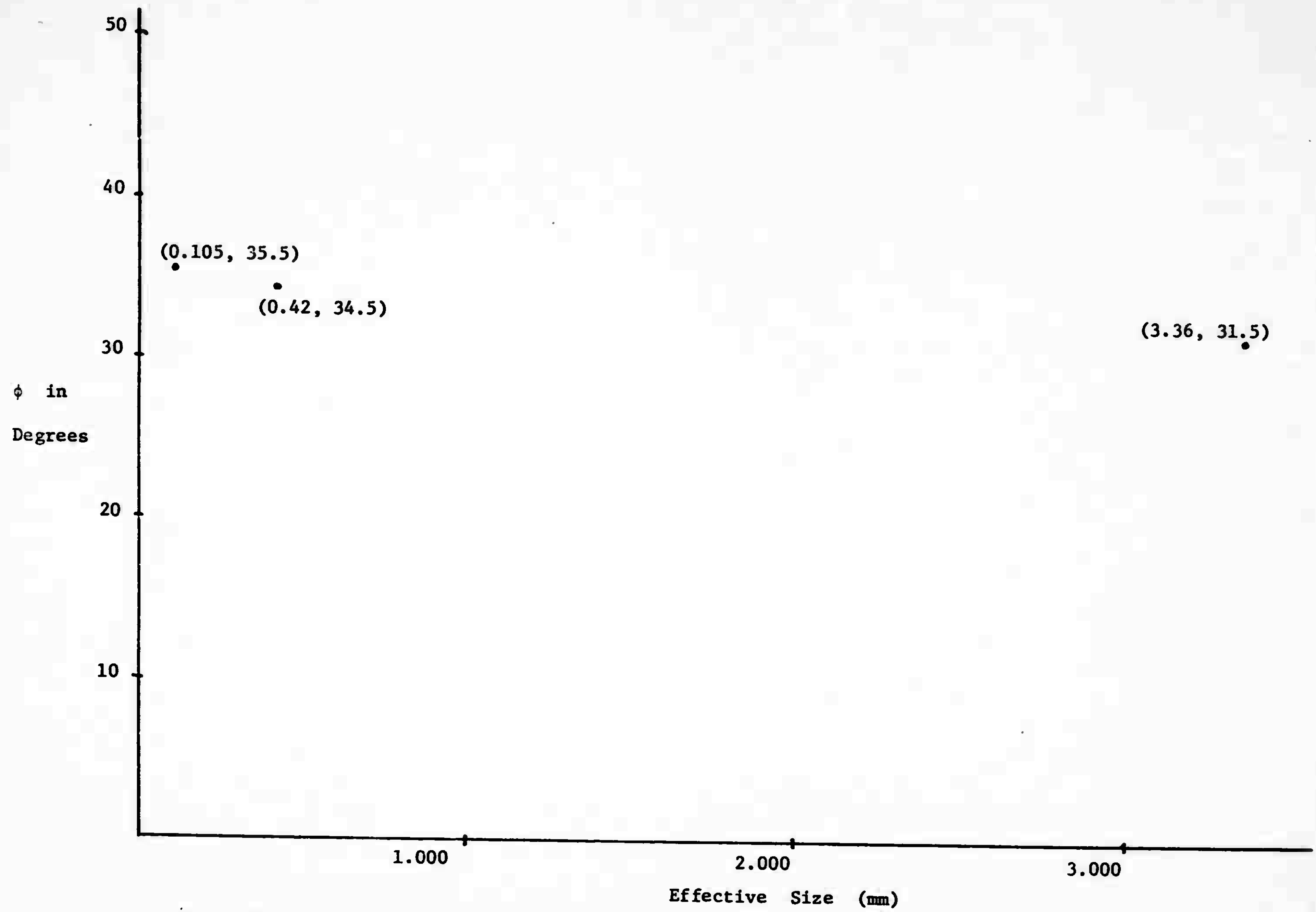

Figure 9. Change in the Angle of Internal Friction with Particle Size.

At first glance the points shown in Figure 9 appear to fit a straight line. A simple linear regression was therefore applied to the points and an equation was obtained. Although the standard deviation of the data points about the "best fit" linear regression line was only 0.4537, much better results were achieved with a quadratic curve. These results will be given here. The "best fit" quadratic equation for the given data points is

$$y = 0.66x^2 - 3.52x + 35.86$$

Table V illustrates how close this equation fits the actual data points.

Actual x Values	Predicted x Values to Fit the Curve	Standard Deviation of Pred. x Values	Actual y Values	Predicted y Values to Fit the Curve	Standard Deviation of Pred. y Values
0.10500	0.10500	0	35.50000	35.49992	0.00011
0.42000	0.42000	0	34.50000	34.49992	0.00011
3.36000	3.36000	0	31.50000	31.50000	0.00011

Table V. Predicted Quadratic Equation Data

The estimated standard deviation of the y values about the regression line is 0.0001, which is considerably better than that of the linear equation.

Due to the limited number of data points available and to the closeness-of-fit of the above equation, higher order regressions were not attempted. However, as the data is developed similar analyses will be performed. Although the literature indicates that the angle of internal friction will drastically rise as the sizes become much smaller than those tested here, further tests of samples on hand propose to examine the variations of the angle in the larger size specimens.

VI. Conclusions and Future Plans

Sieve analyses indicate that disc cutters on tunnel boring machines are better than button roller cutters. Since more energy is needed to crush rock to small fragments than to chip out large fragments, disc cutters are preferable. Mucking and handling large particles is also more convenient than handling very small particles. If the material in question is clayey or cohesive, the addition of water might lower the strength of the material. The Heber City samples tested are a good example of that. Muck of this type clogs conveyor systems and sticks to mucking equipment making operation difficult.

Some of the rocks tested show a change in the angle of internal friction with a variation in size. It appears that the angle does increase as the size decreases. The only sample that shows no change in the angle of internal friction with size is the Heber City sample, which shows no strength at all. It has not yet been determined what happens as the particles become larger than 6 mesh since serious problems with membrane puncture were encountered here. This problem will have to be solved during the second year of funding.

Future plans include another sample gathering trip this summer. The purpose of the trip will be to provide data to fill existing gaps such as the limited variation of rock types now on hand. It is hoped that several days might be spent at some of the tunnels in order to obtain a variety of samples. Samples taken at different machine thrusts and rotation speeds should show a variation in the angle of internal friction. When more data are accumulated from testing these new samples, a factor analysis will be done to determine whether variation

in machine parameters are as important as lithologic type in setting the angle of internal friction (Saperstein, 1971). Use of the shear box in Pittsburgh on various sample sizes will be employed to correlate with the triaxial testing results.

Year two will also investigate the effect of wetting agents other than water on the angle of internal friction. Many detergent base fluids, as well as other fluids, are being used to lay dust and, sometimes, to improve the penetration process. Samples with known angles of internal friction will be wetted with these fluids and then tested for possible variation in the angle of internal friction. As experience is gained with variation of ϕ through single size ranges, tests will be made to determine the variation of ϕ with sets of size ranges. That is material will be formulated to contain more than one size and the ratios of these sizes will be varied. These tests mean that there will be ultimately a variation of size consist. Within a short period a visit will be made to a tunnel with a variable speed cutting head and it may be possible to obtain samples with a machine-varied size consist.

It is expected that by the end of year two conclusions might be made concerning changes in the angle of internal friction. These conclusions will include a statement concerning the potential of altering size consist and the angle of internal friction by changing machine parameters, or by the additive use of certain wetting agents (Saperstein, 1971).

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VIII Appendices

Appendix I

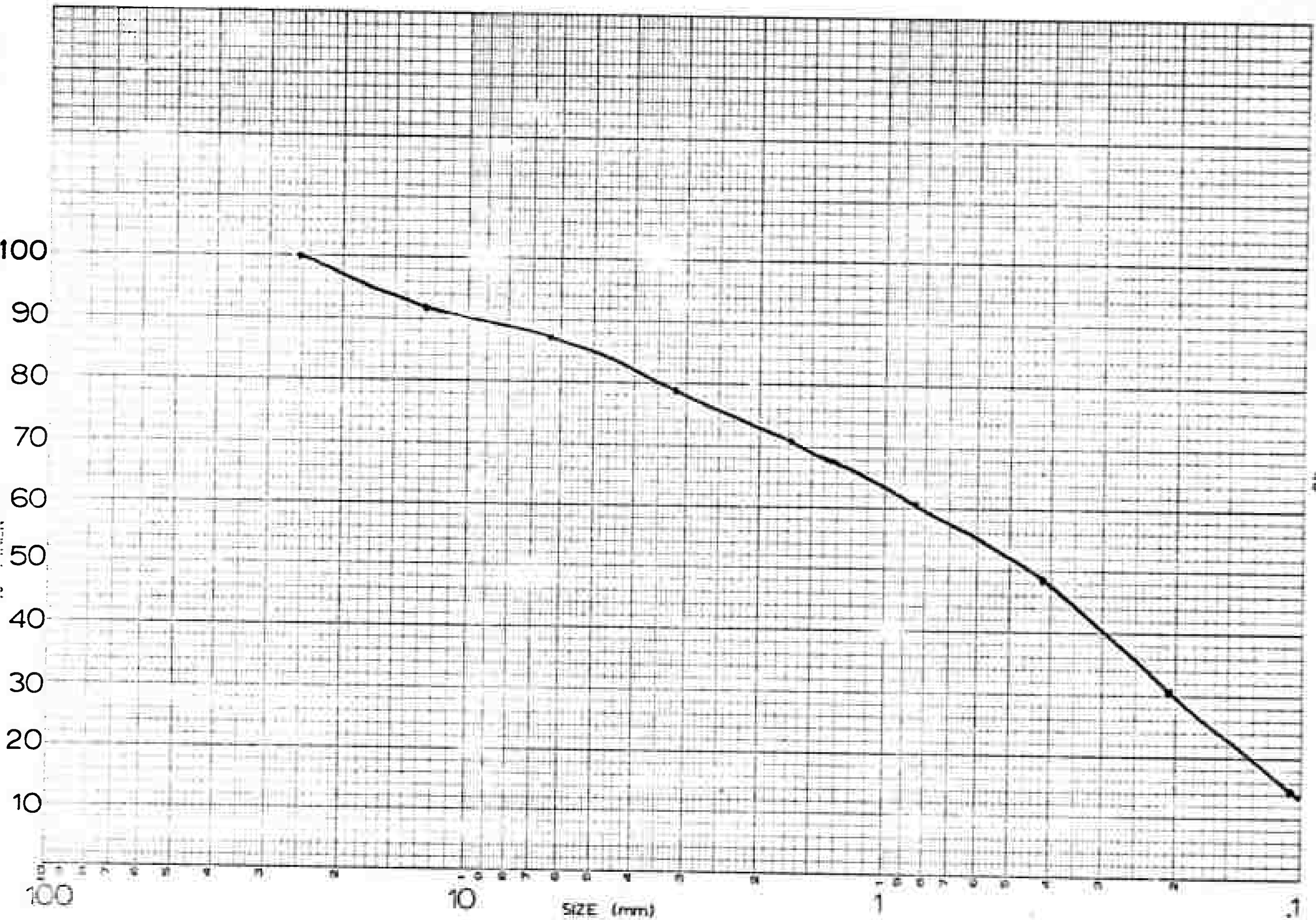
Tunnel Locations and Data

	Phila-delphia	Chicago	Heber City	Farming-ton	Aspen	White Pine	Toronto
Date of Visit	6-24-71	7-16-71	7-19-71	7-21-71	7-22-71	7-26-71	7-27-71
Outer Diameter	11'	13' 8"	12' 11"	20' 6"	10'	18' 2"	12'
Lined Diameter	8'	-	10' 4"	18'	Only in Bad Ground	Unlined	10'
Length to Date	4100'	19,500'	1200'	1700'	2800'	4800'	2-1/2 mi.
Length Total	5800'	22,000'	17,355'	3.5 mi.	16,800'	2 mi.	15,200'
Best Shift	40'	49.4'	67'	65'	40'	24'	?
Best Day	89'	111.3'	176'	178'	60'	44'	?
Number of Men	4	7	6	12	8	6	?
Machine	Jarva Mark 4	Lawrence 0007	Robbins 141-127	Dresser	Wirth	Robbins 181-122	Robbins 126
Horsepower	500	750	600	700	600	800	500
Cutters	27 disc kerf	27 disc w/button mount	29 disc	36 double disc	26 button roller	47 disc	25-30 disc
Rotation RPM	10	9	3 or 6	6	8	4.5	5-10
Thrust	1,200,000	1,500,000	750,000	850,000	1600 psi pump pressure	1,200,000	?
Spray (GPM)	5	40	2-3	None	26	15	?
Conveyor Width	18"	24"	30"	30"	24"	30"	?
Rock Type	Mica Schist	Dolomitic Limestone	Sand-stone	Sand-stone	Granite	Sand-stone	Shale
Sample % Moisture	14.926	8.411	14.447	-	21.975	-	-

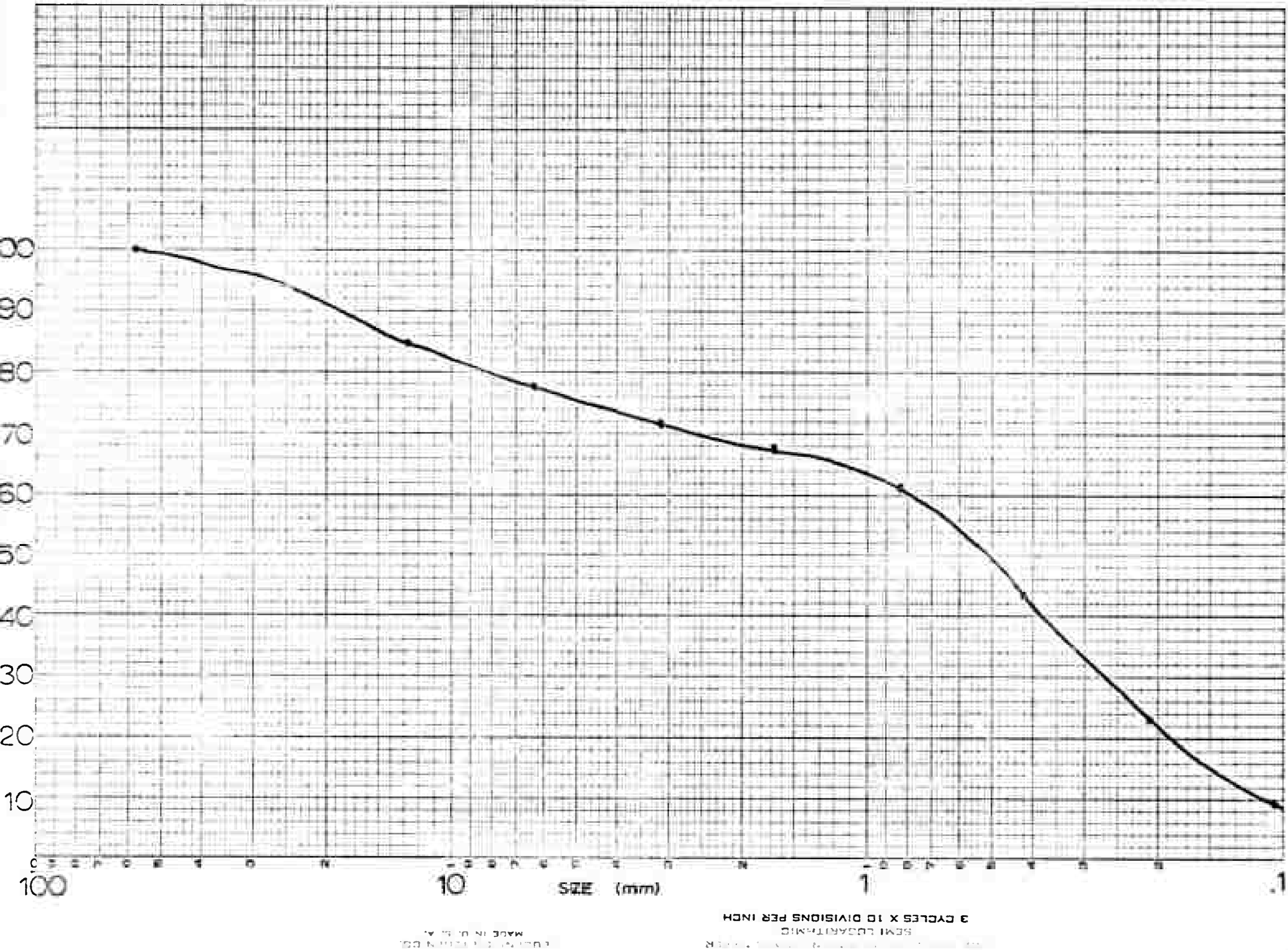
Appendix II

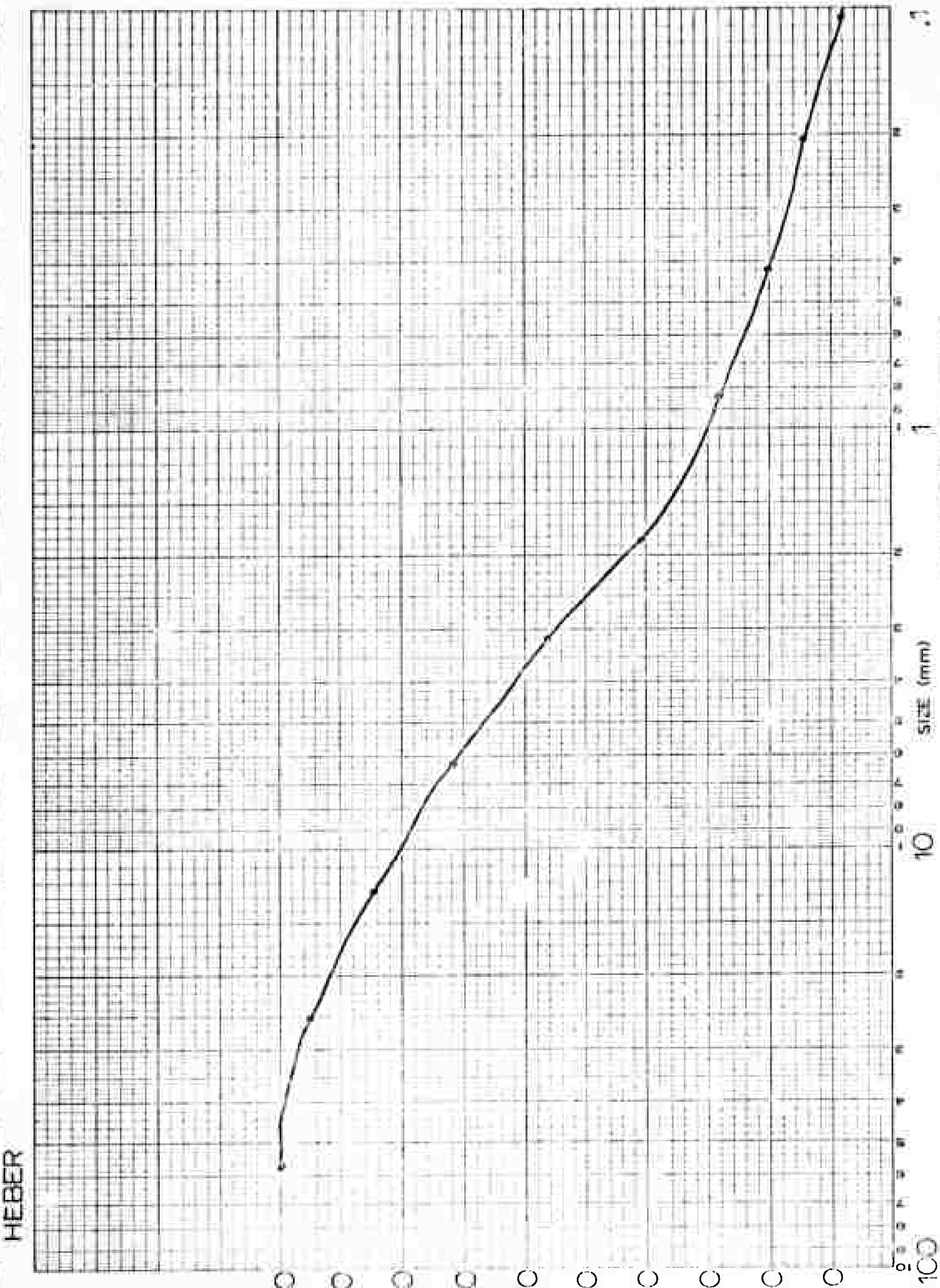
Gradation of Each Sample

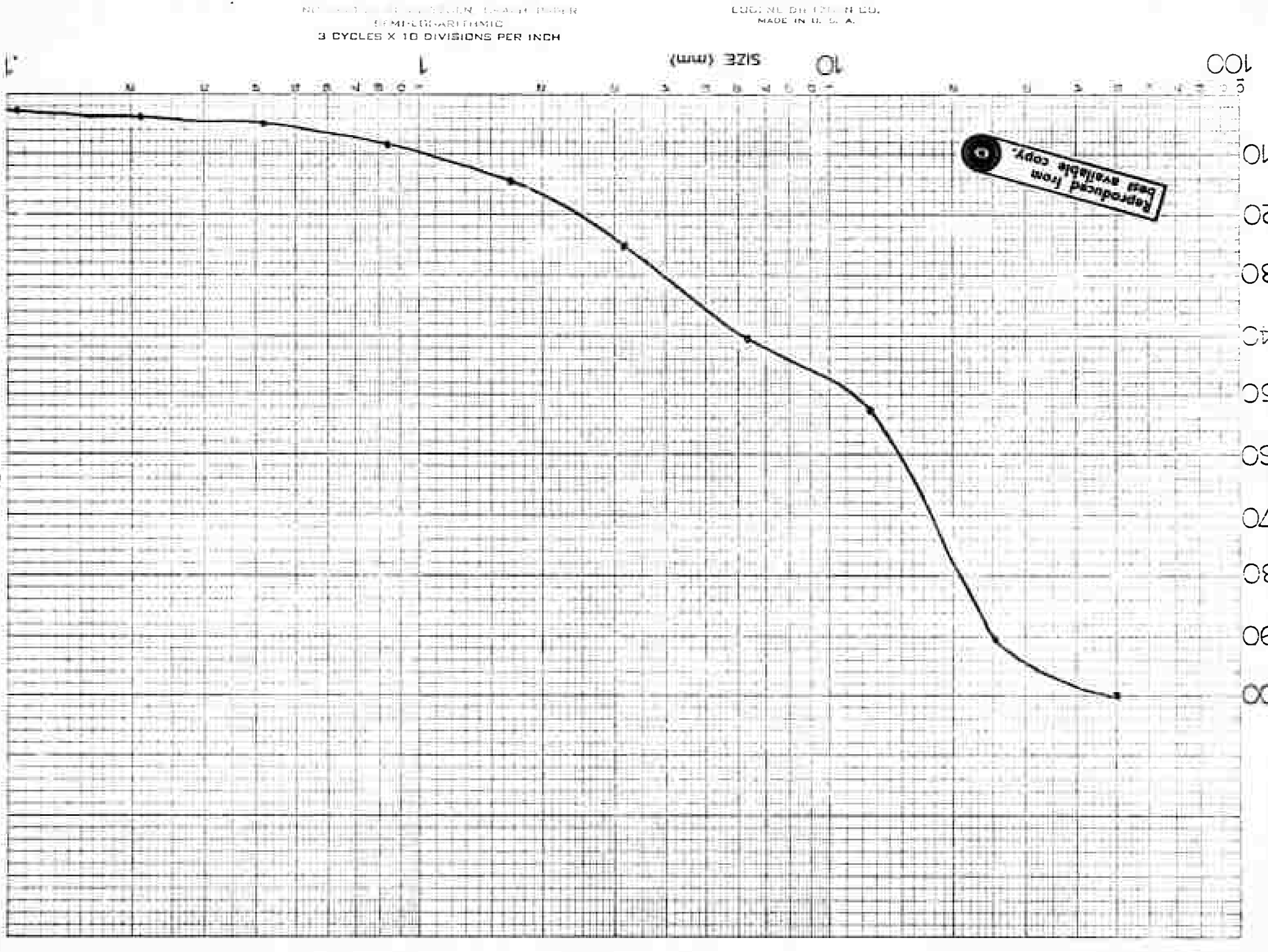
PHILADELPHIA



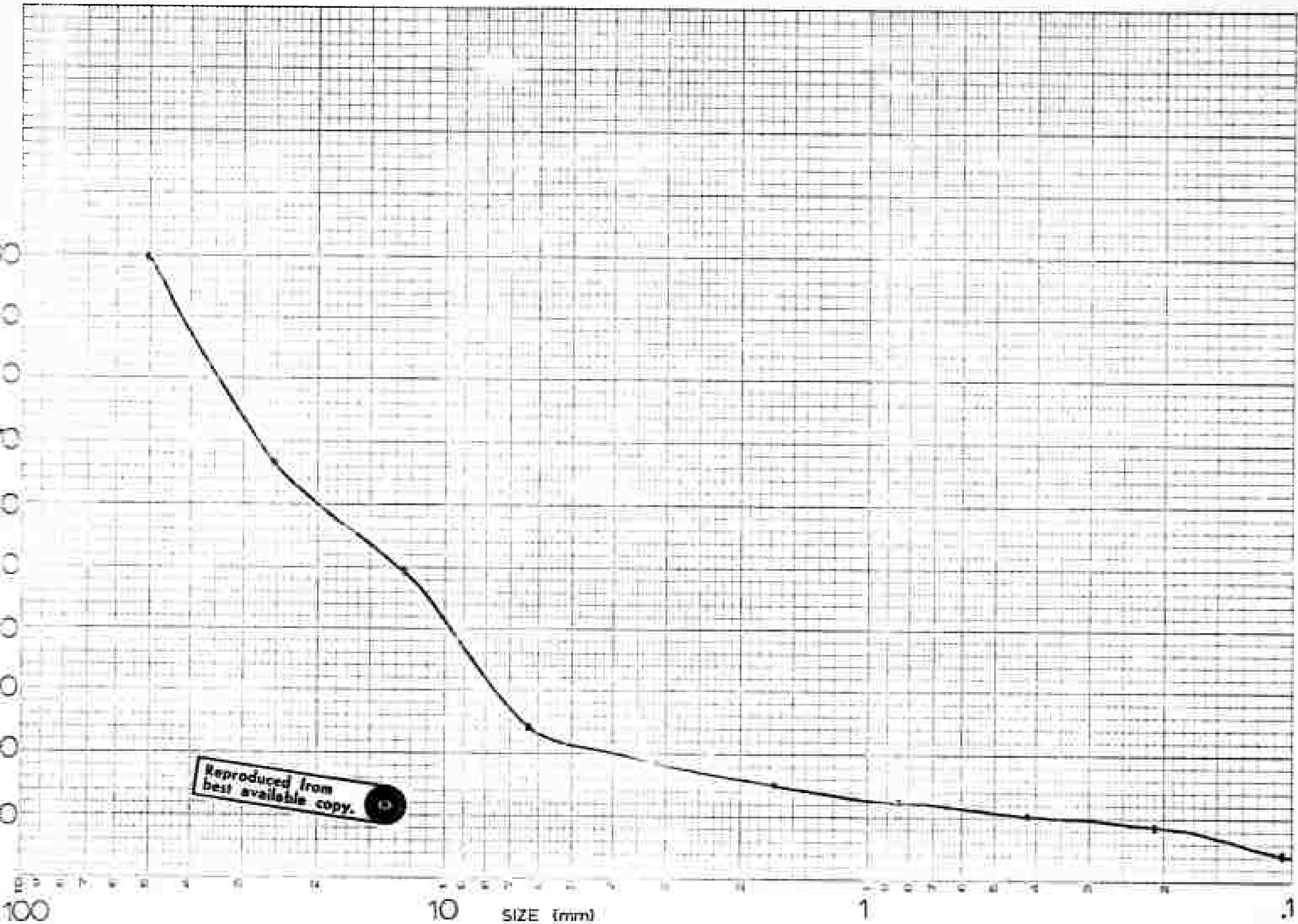
FARMINGTON

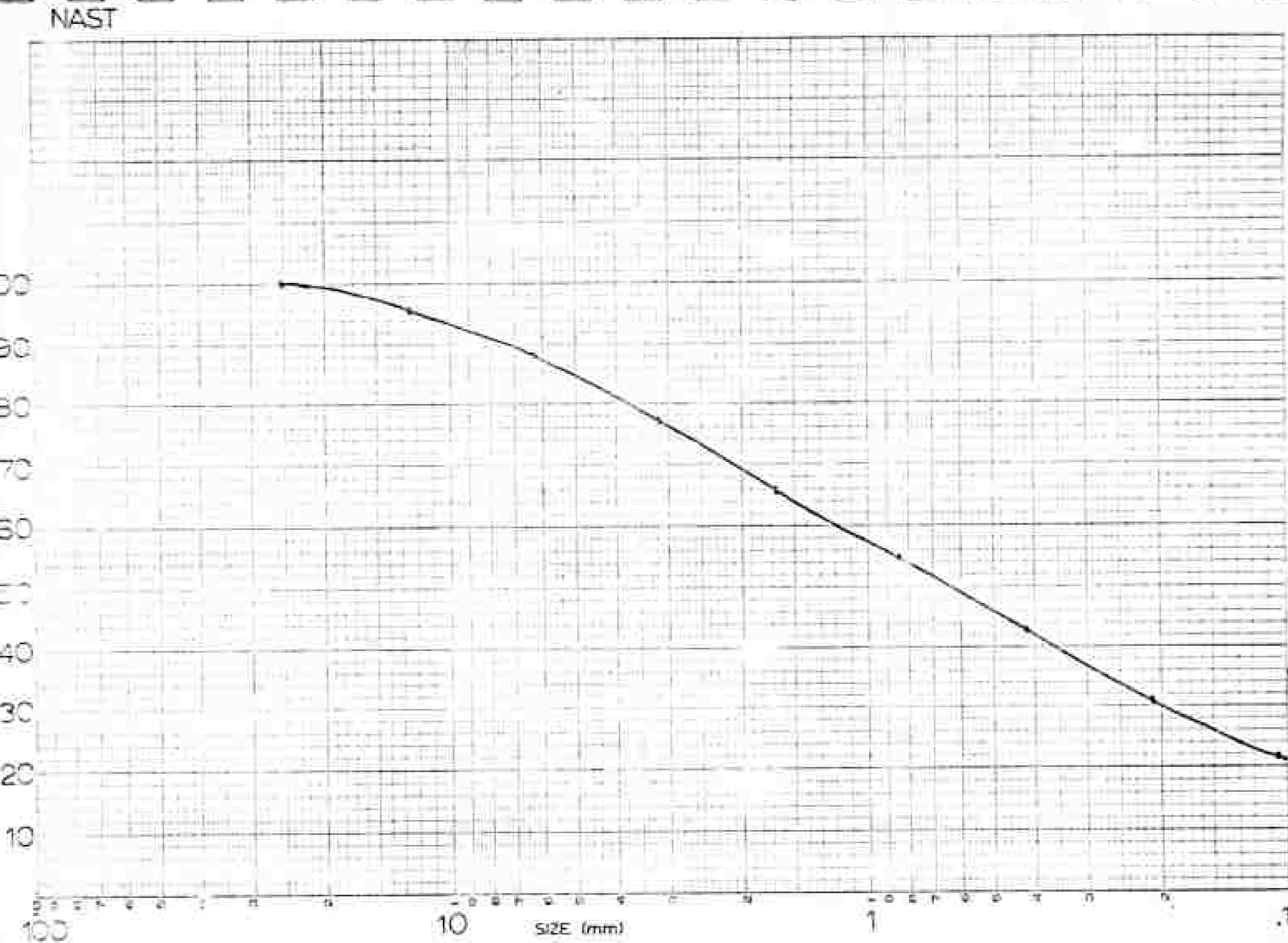

100
90
80
70
60
50
40
30
20
10
100
10
1
.1
SIZE (mm)
3 CYCLES X 10 DIVISIONS PER INCH
SEMI LOGARITHMIC
MADE IN U.S.A.


HEBER
SIZE (mm)
10
1


SEMI-LOGARITHMIC
3 CYCLES X 10 DIVISIONS PER INCH
MADE IN U. S. A.
SIZE (mm)
.1
1
10
100
10
20
30
40
50
60
70
80
90
TORONTO
Reproduced from best available copy.

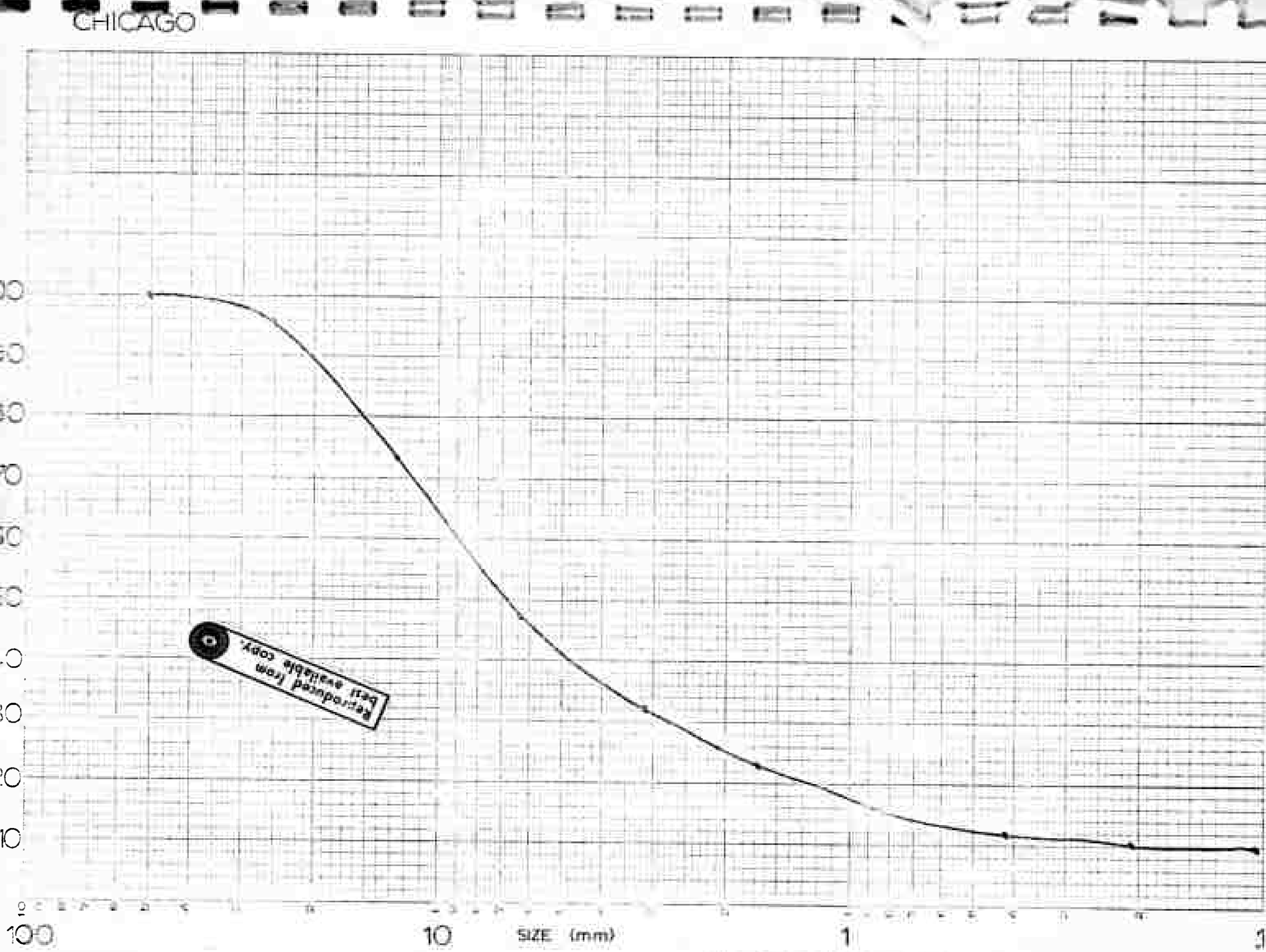
WHITE PINE





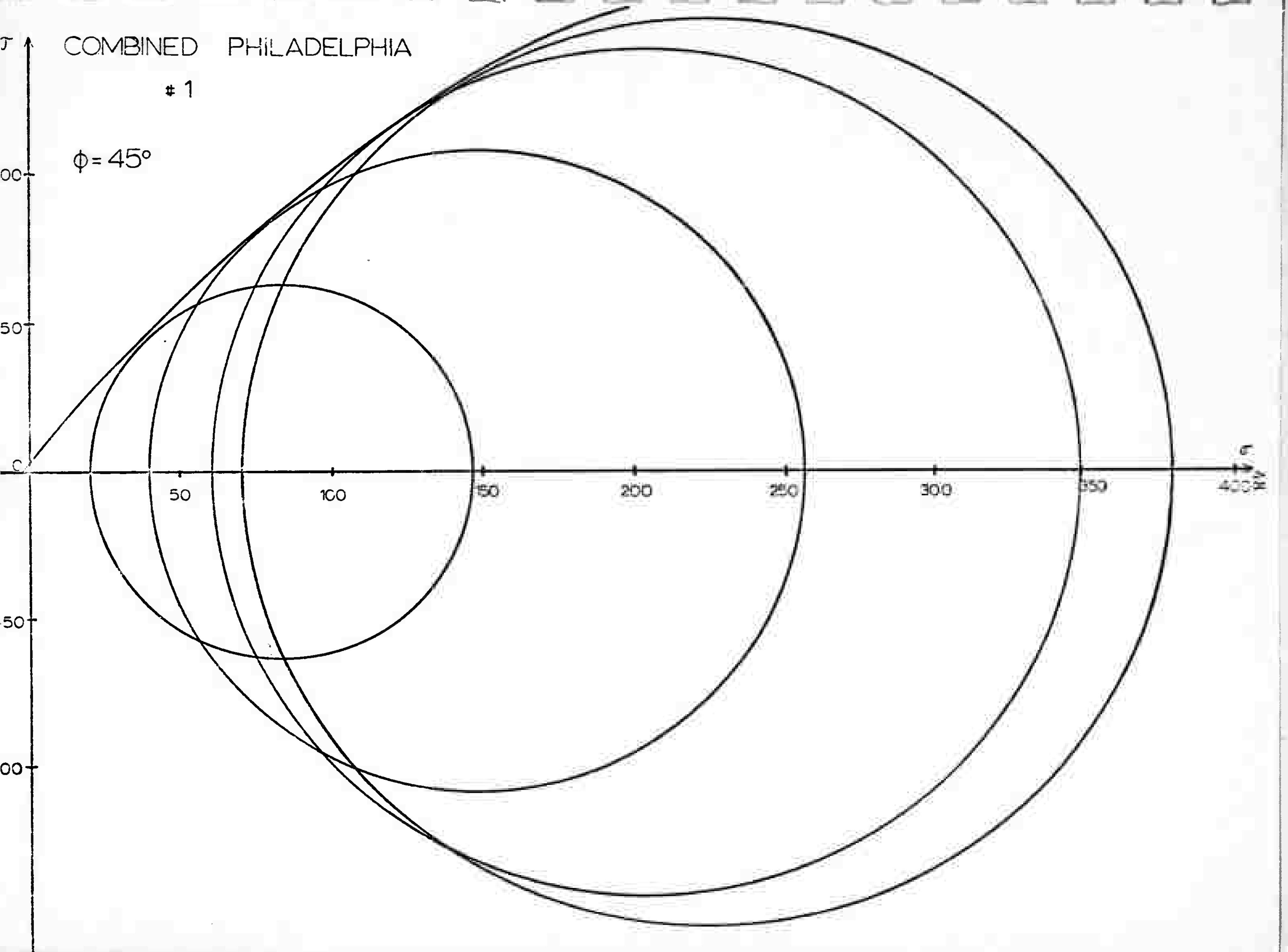
[redacted] 45 [redacted]

[redacted] #6



Appendix III

Mohr's Envelope for Each Sample


COMBINED PHILADELPHIA
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$\phi = 45°$
τ
σ
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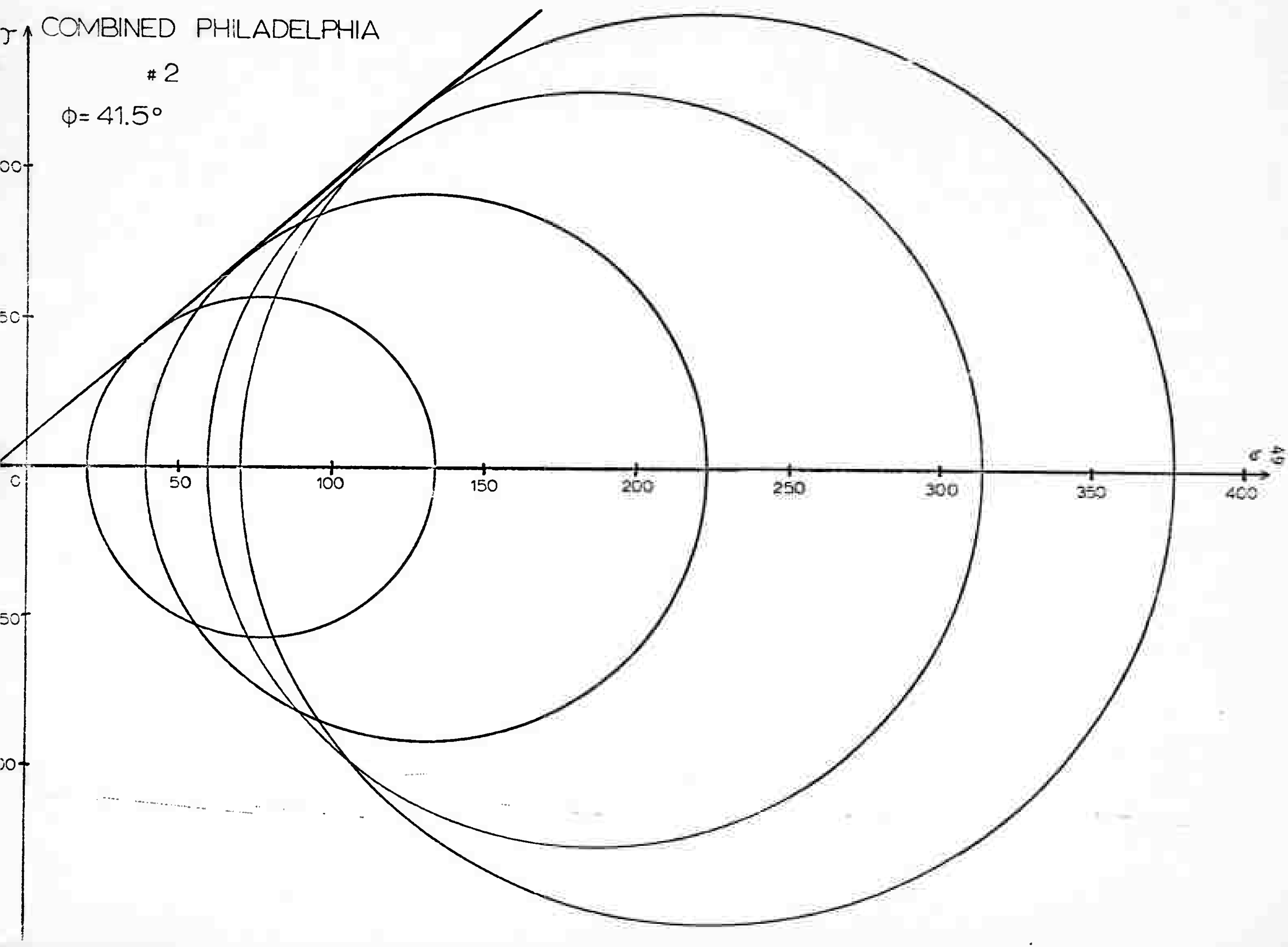
50
100
150
200
250
300
350
400



COMBINED PHILADELPHIA
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τ
σ
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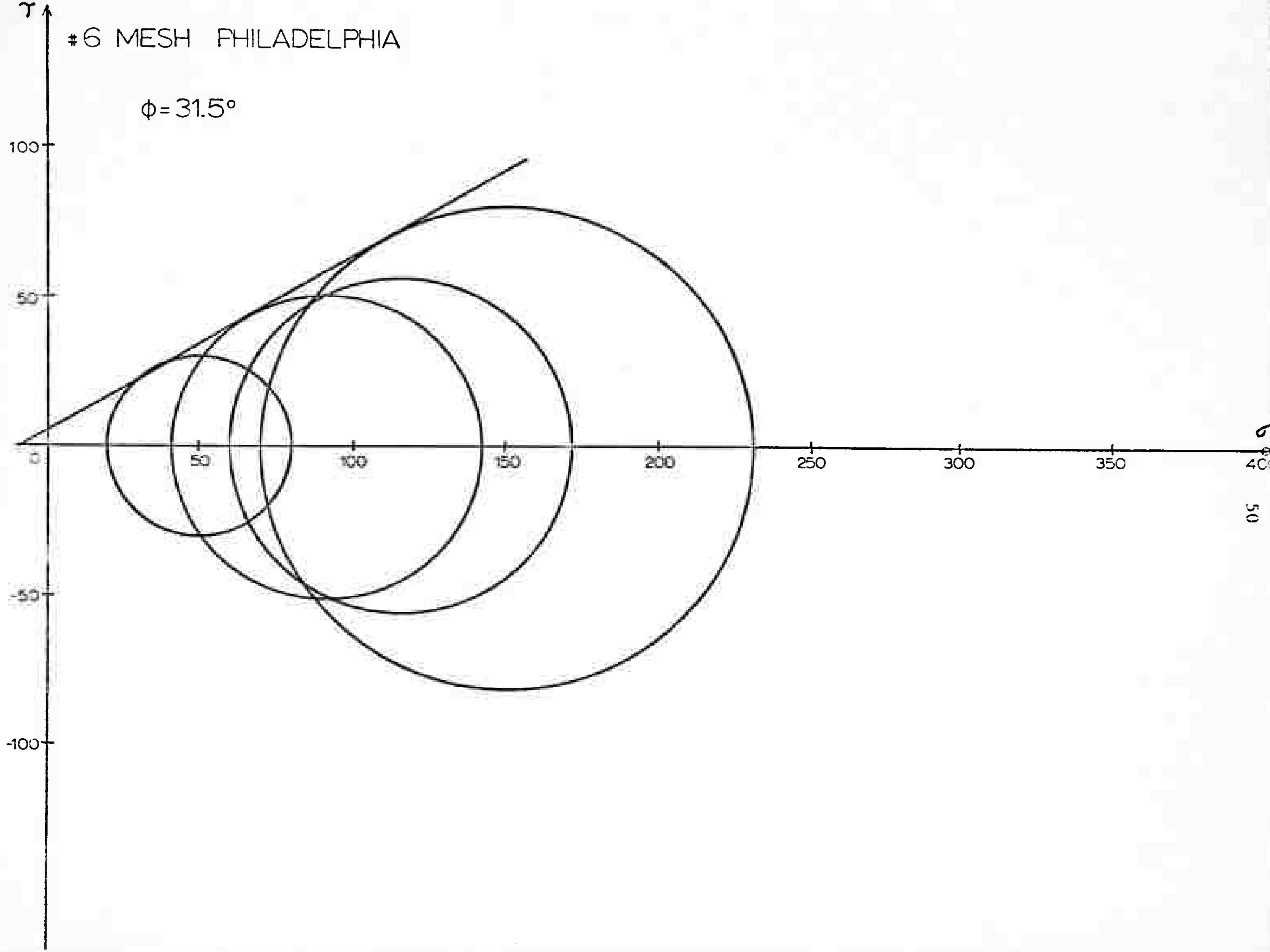
50
100
150
200
250
300
350
400


#6 MESH PHILADELPHIA
$\phi = 31.5°$
τ
σ
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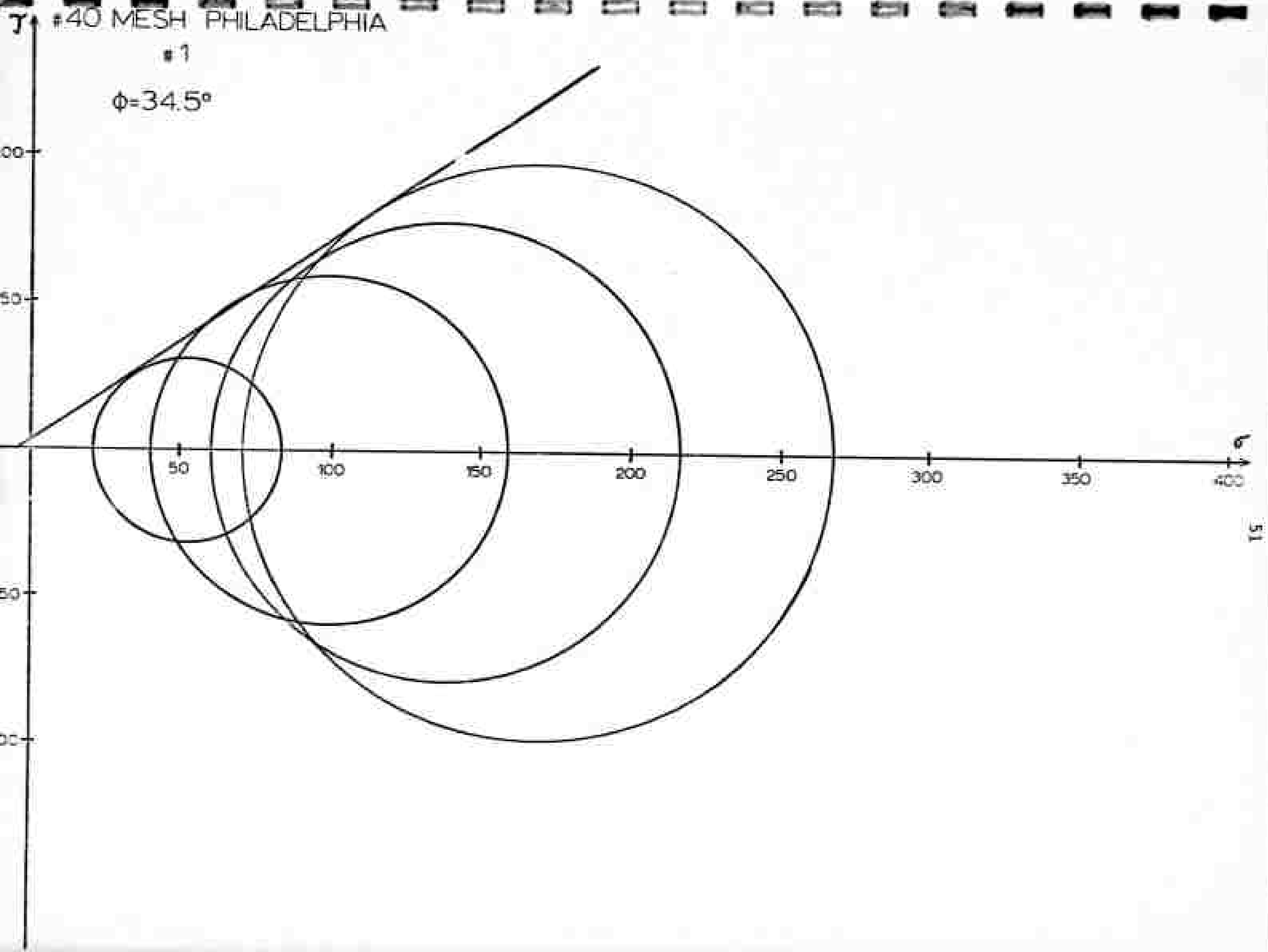
50
0
-50
-100
50
100
150
200
250
300
350
400



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τ
σ
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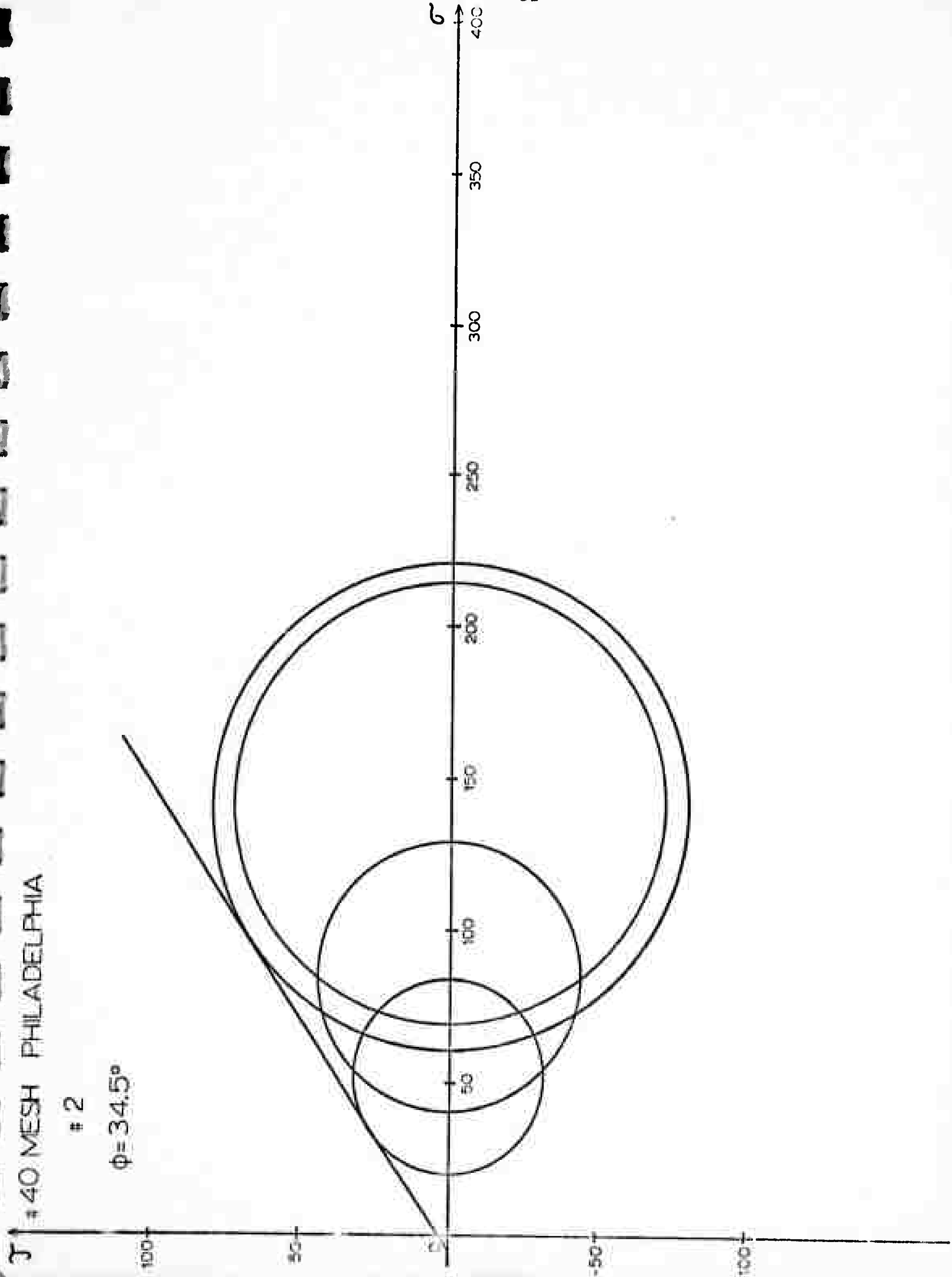
150
200
250
300
350
400



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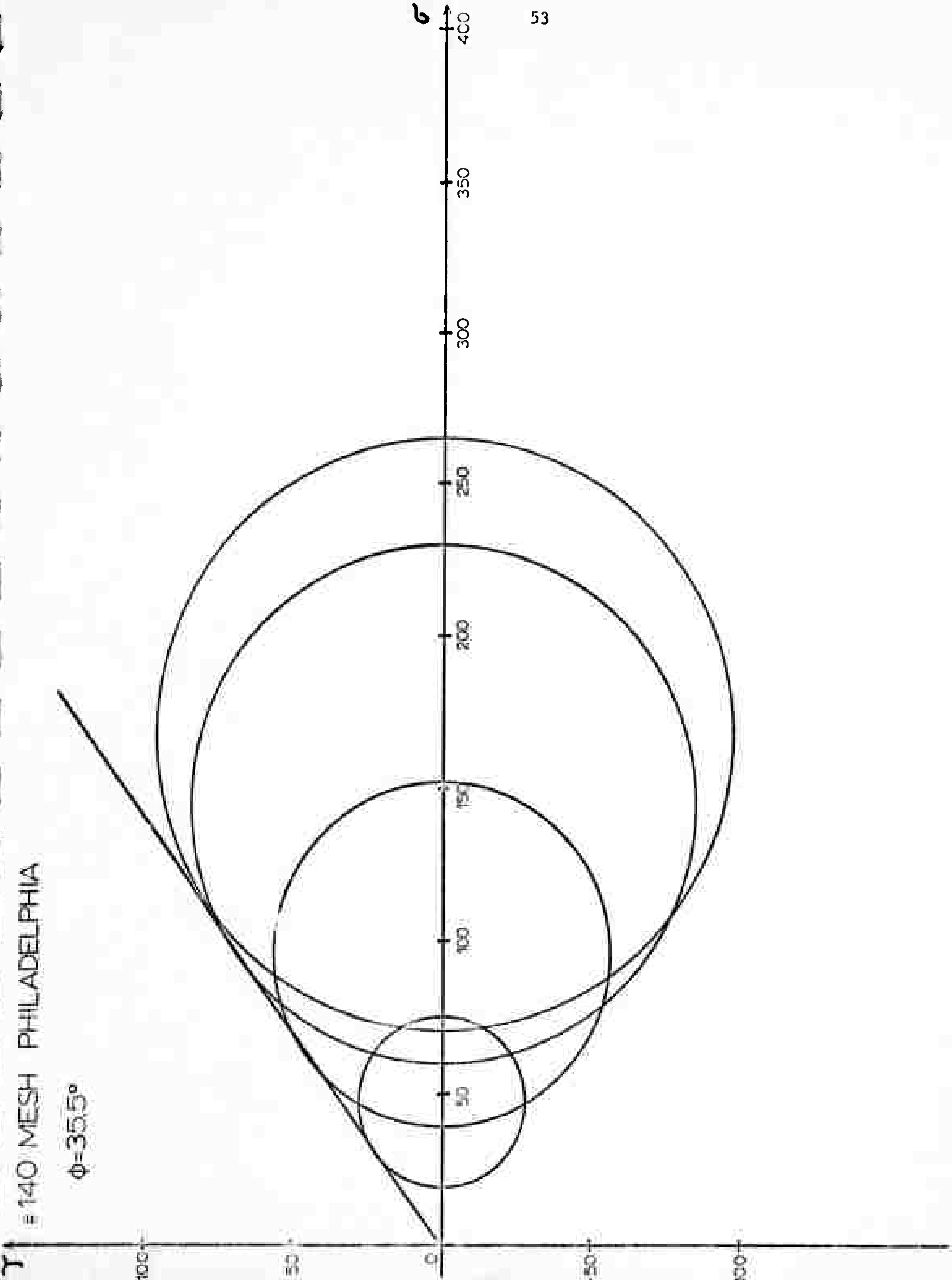
-100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τ
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100
150
200
250
300
350
400
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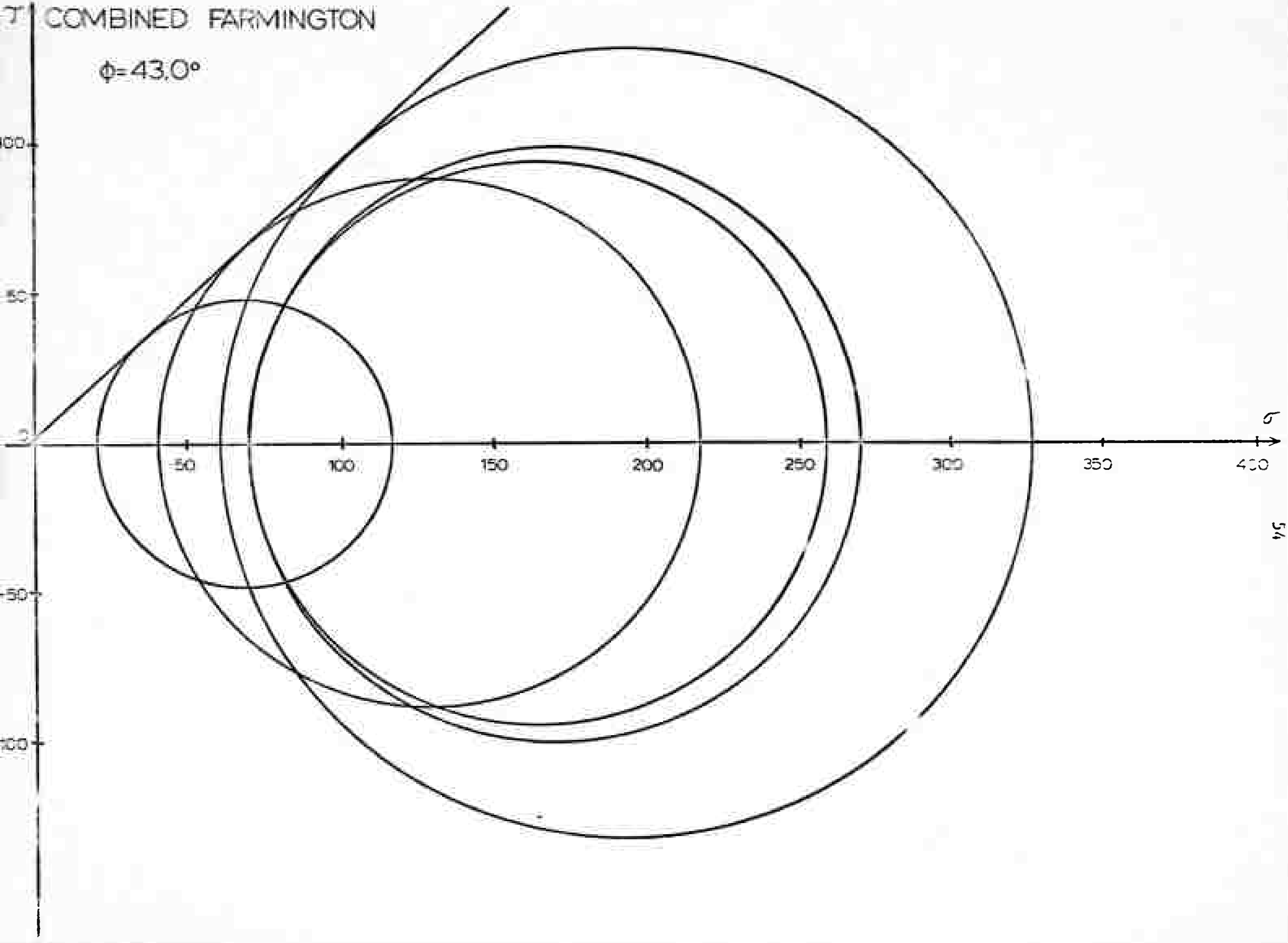
50
0
-50
-100



τ
COMBINED FARMINGTON
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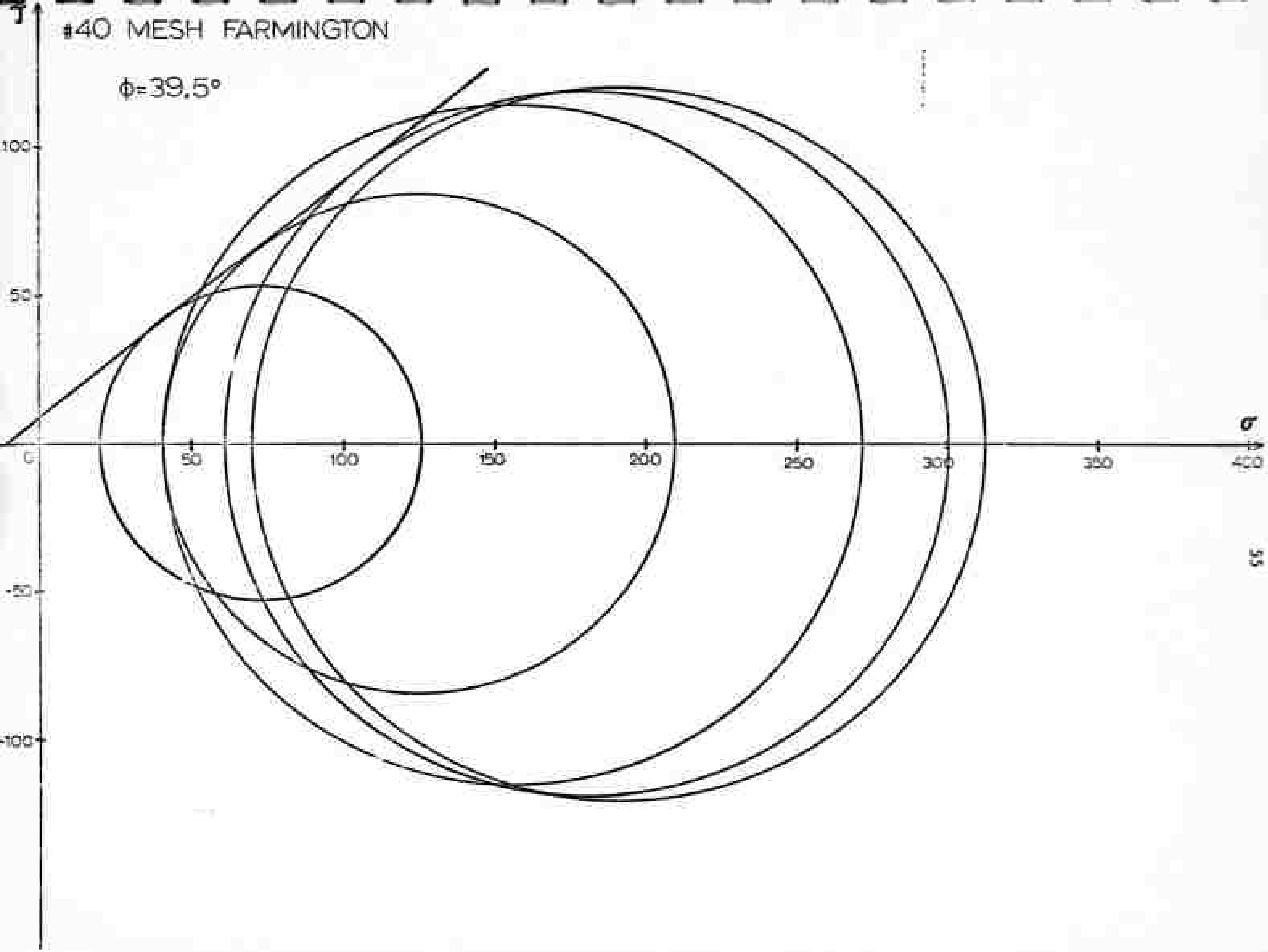
50
0
-50
-100
σ
50
100
150
200
250
300
350
400



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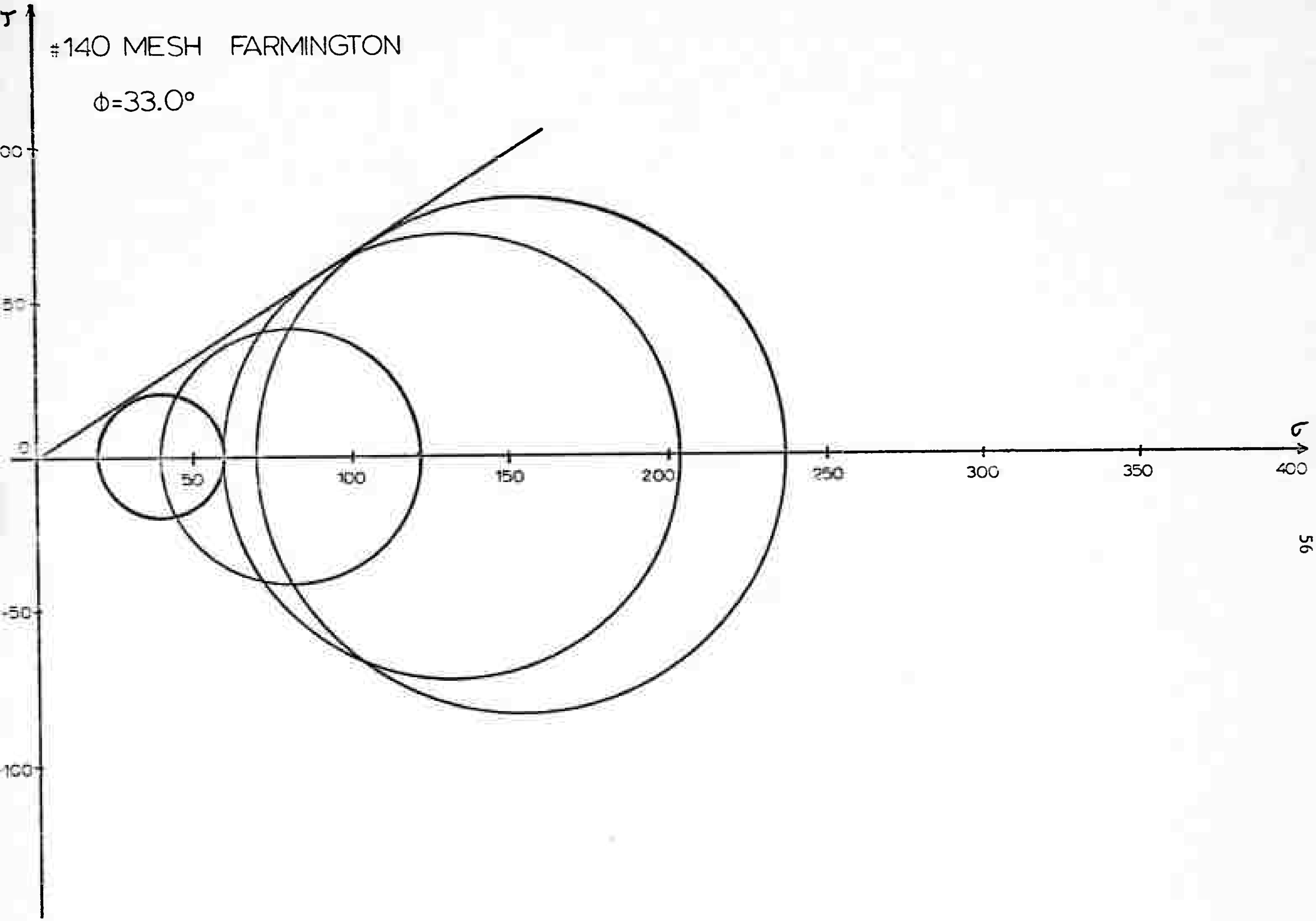
-50
-100
50
100
150
200
250
300
350
400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τ
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200
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400
-50
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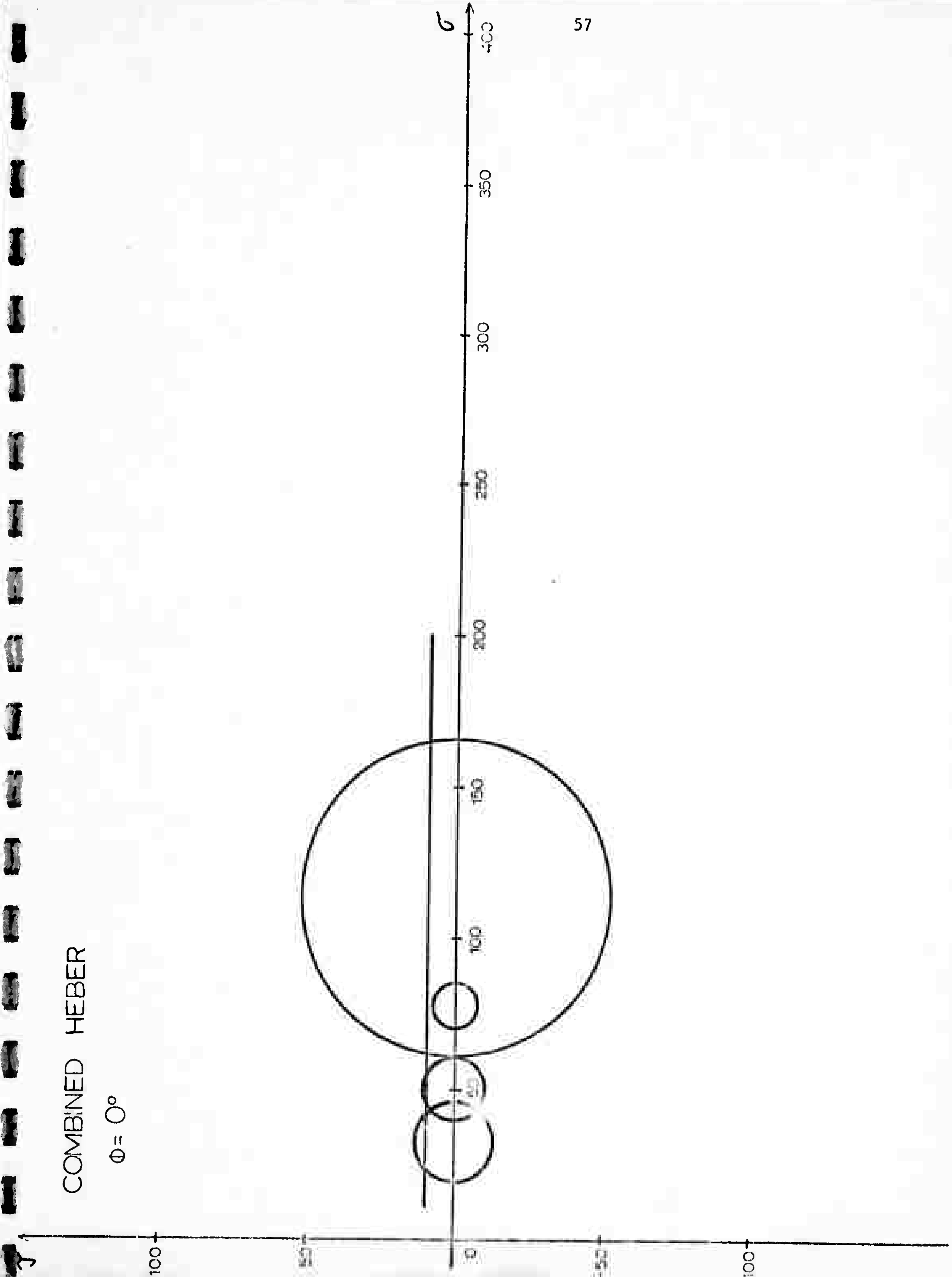
COMBINED HEBER
Φ = 0°
σ
τ
400
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300
250
200
150
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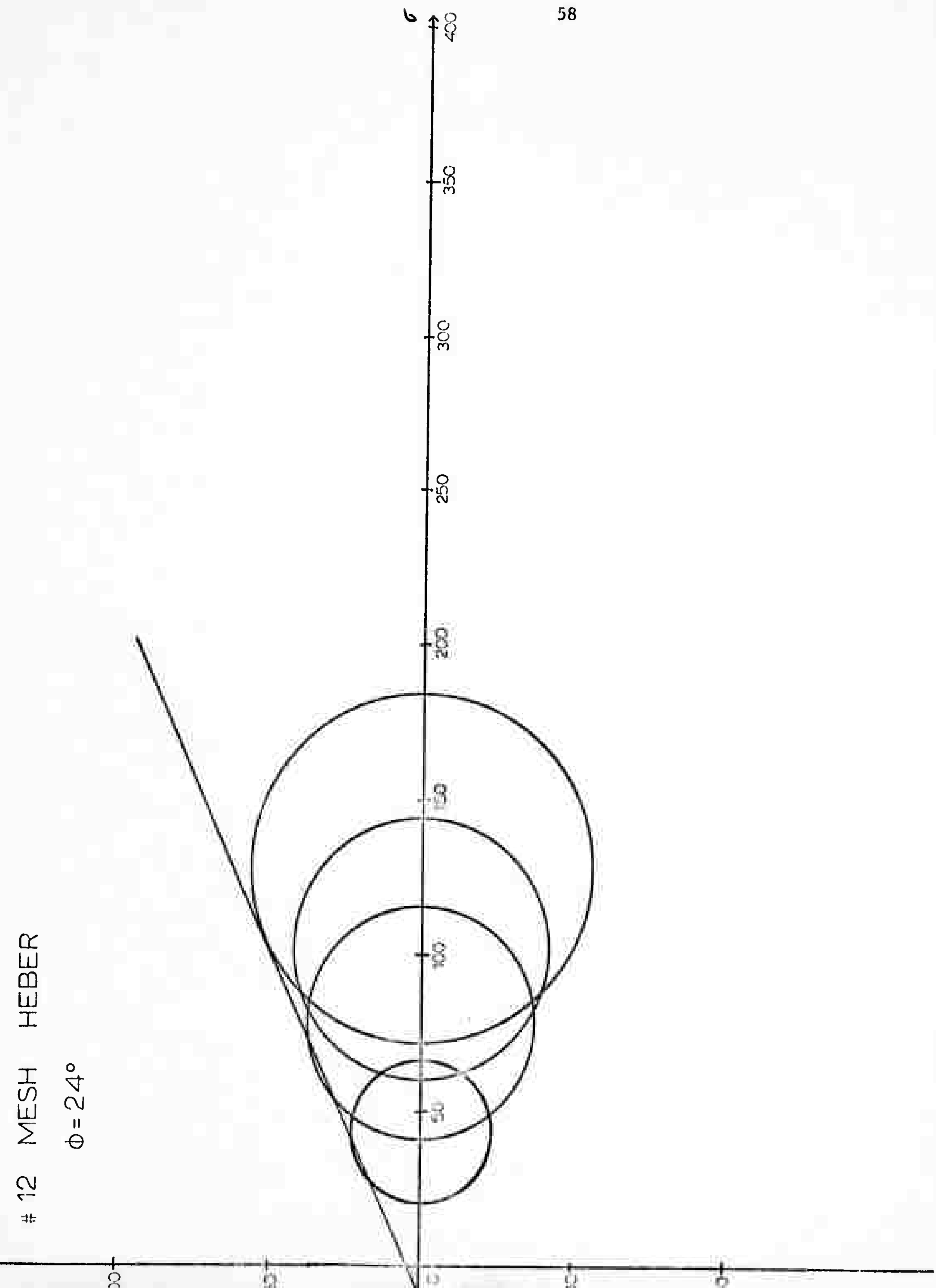
100
50
0
-50
-100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σ
400
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300
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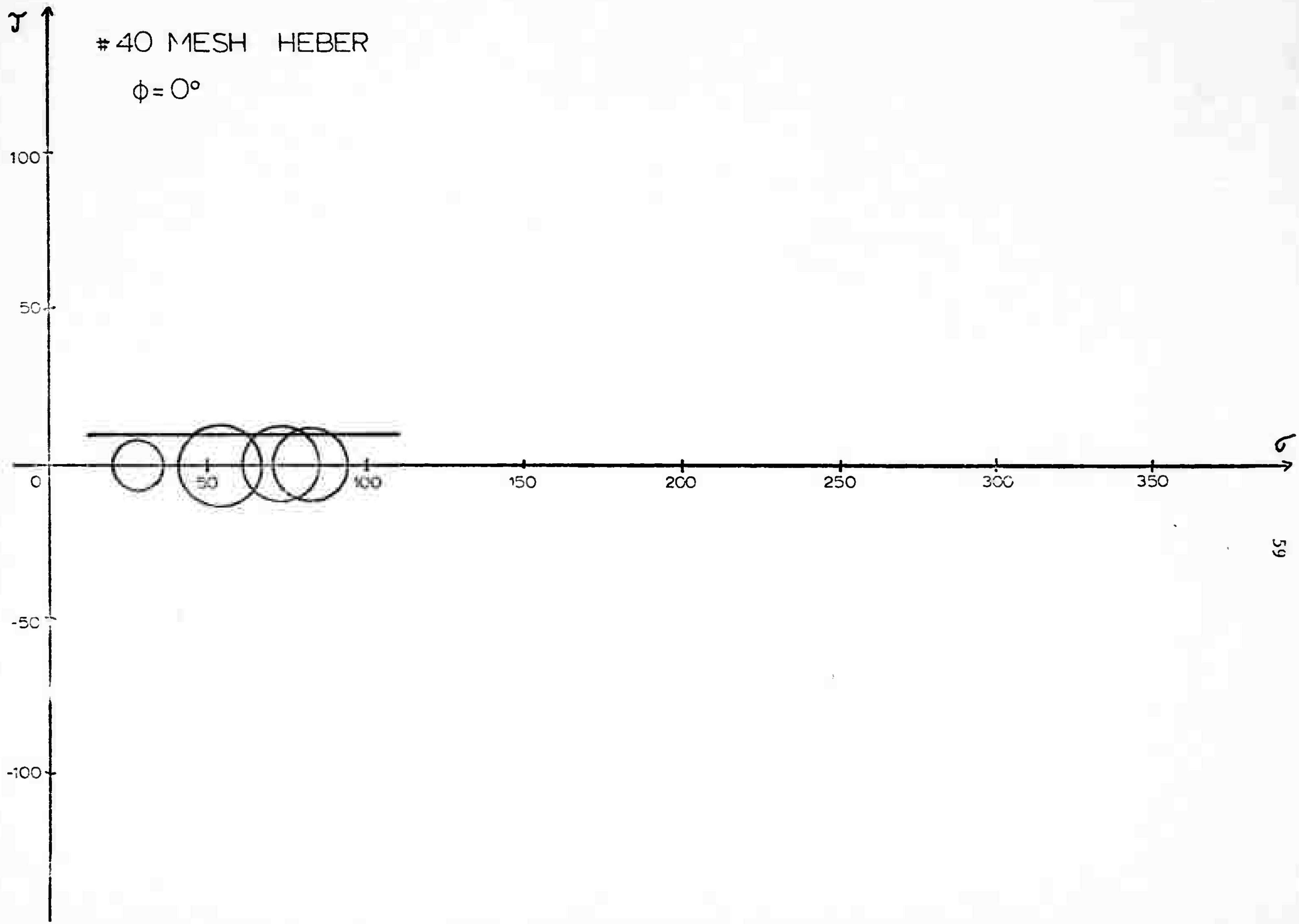
200
150
100
50
τ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τ
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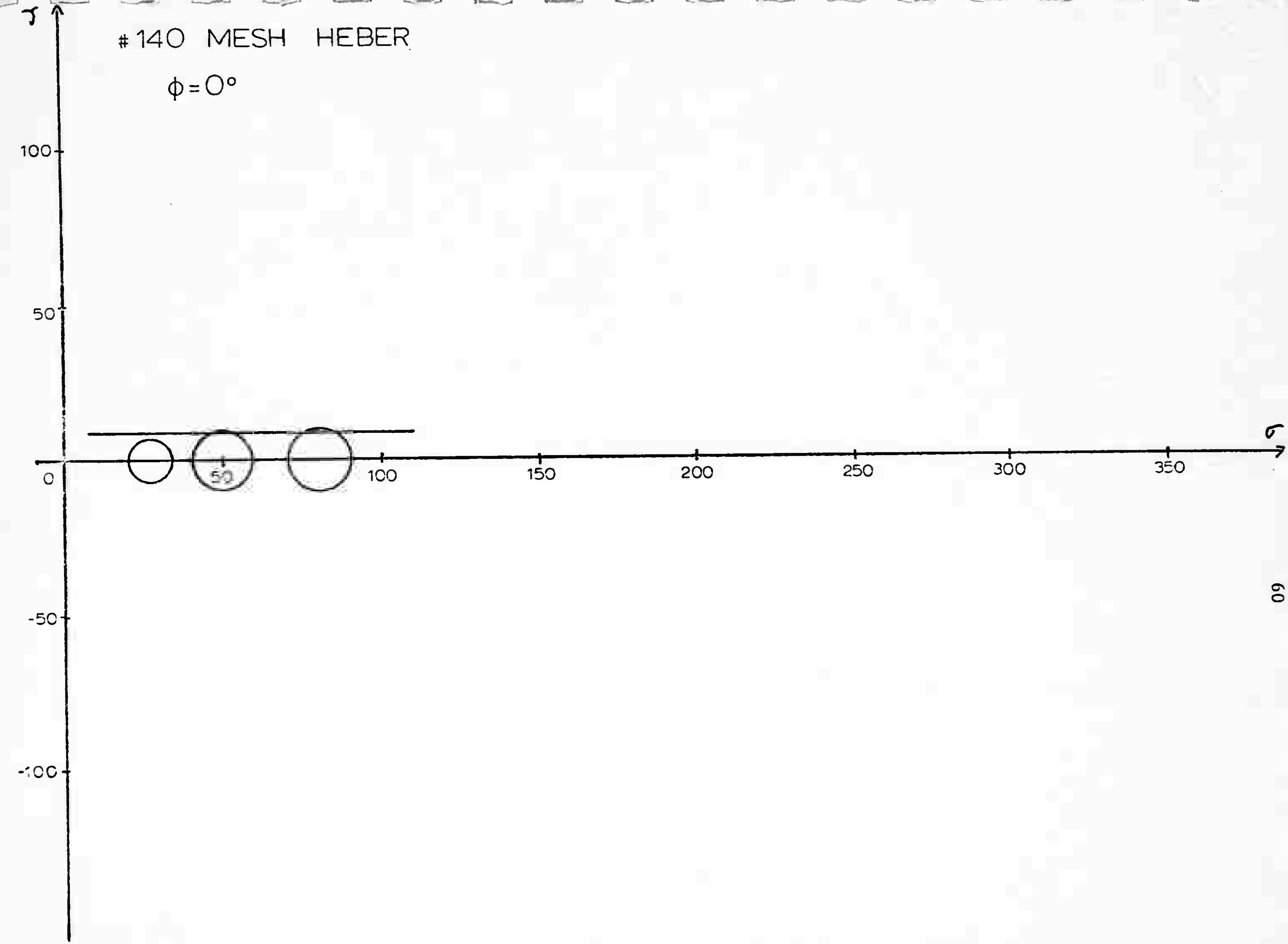
-50
-100
50
100
150
200
250
300
350



140 MESH HEBER
$\phi = 0°$
τ
σ
100
50
0
-50
-100
50
100
150
200
250
300
350

Appendix IV

Table of Mohr's Circle Data

	Philadelphia		Farmington		Heber City	
	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
Combined	20	148.4	20	113.9	20	46.7
	40	253.9	40	219.4	40	59.9
	60	348.2	60	327.8	60	166.3
	70	380.3	70	270.2	70	84.9
	20	134.7	70	259.4		
	40	222.0				
	60	314.8				
	70	378.4				
# 6 Mesh	20	80.1				
	40	142.1				
	60	170.2				
	70	232.8				
# 12 Mesh					20	66.2
					40	115.9
					60	143.3
					70	184.1
# 40 Mesh	20	83.4	20	123.3	20	33.2
	40	128.7	40	210.4	40	63.9
	40	154.6	40	272.1	60	84.1
	60	220.7	60	301.9	70	92.4
	60	217.8	70	312.5		
	70	215.4				
	70	268.8				
# 140 Mesh	20	76.6	20	59.8	20	31.8
	40	151.0	40	121.7	40	59.5
	60	229.1	60	204.9	60	60.0
	70	266.4	70	238.3	70	86.9